REMARKS

The application is believed to be in condition for allowance.

Claims 2, 6, 8-16, and 20 stand rejected under §112, first paragraph, as failing to comply with the enablement requirement (sic). Applicants respectfully disagree, but cancel the objected-to subject matter, without prejudice, in order to advance the case.

Claim 17 has been amended to make explicit that the test is to determine whether the line is suitable for xDSL transmission use.

The Official Action rejected claims 1-20 as obvious over KOEMAN et al. 5,731,706 in view of VALENTI et al (US 2002/0041565).

By way of review, the present invention concerns xDSL and existing cross-talk noise caused by other subscriber telephone lines, e.g., digital signals carried thereon. As shown in Figure 2 of the present application, a voltage measurement is made across the T and R connections of the subscriber telephone line.

The invention tests the telephone lines for cross-talk existing on the telephone line due to interference from other subscriber telephone lines within the frequency range delimited

by xDSL use. The present invention need not look outside the xDSL frequency range as those frequencies are of no interest.

The Official Action, admits on page 4, that KOEMAN et al. does not consider the xDSL frequency range because KOEMAN et al. is to be used during installation phase enabling installers the ability to verify proper transmission performance of wire pairs.

Indeed, KOEMAN et al. is not seen to poll an xDSL circuit as KOEMAN et al. polls a LAN circuit. The LAN circuit is not an xDSL circuit. Furhter, KOEMAN et al. discloses testing the quality of a ***LAN cable system*** by injecting ***a pulse signal*** into the telephone line and measuring a response signal so as to assess the quality of the LAN cable system in the frequency appropriate to LAN signals. See KOEMAN et al. Figure 5 disclosing source signal generator 202 with pulse generator 206 providing a stimulus signal into the LAN cable system 14 and receiver 208 measuring the responsive signal.

In contrast, the present invention measures cross-talk, within the xDSL frequency, caused by cross-talk from adjacent subscriber lines within the frequency range of interest.

KOEMAN et al. is not concerned with the xDSL frequency bands and thus teaches to measure beyond the xDSL frequency and up to 100 MHz as KOEMAN et al. See KOEMAN et al.'s use a range of 1 to 100 MHz. See column 2, lines 56-63 indicating sampling

at .15 and .25 MHz intervals over the range 1 MHz through 100 MHz. The tests are driven by the TIA standard TSB 76 (column 2, lines 4-9).

KOEMAN et al. tests outside the range of xDSL use and beyond the range recited in the claims. There is no teaching in KOEMAN et al. to perform tests within the limited, recited range of the pending claims.

The Official Action proposes to modify KOEMAN et al. to be a tester for cross-talk after the installation phase (in-service and/or existing service lines) based on VALENTI.

For measuring cross-talk within the limited xDSL frequency range, VALENTI Figures 5-7 and Table 2 are offered.

Without commenting as to the merit of the Official Action's position, note, however, that the present application claims priority to Japanese Application No. 2000-311045, filed October 11, 2000. Enclosed is a verified English-language translation of that application, which translation perfects Applications' claim to that priority date.

See that VALENTI claims priority to U.S. Provisional Applications 60/222,734, filed August 3, 2000 and 60/262,548, filed January 17, 2001.

It is only the subject matter of U.S. 60/222,734 which is prior art to the present application.

Applicants find that the passages, tables, and figures upon which the Official Action relies are not found in U.S. 60/222,734 and are at best taken from U.S. 60/262,548 which is not prior art to the present application.

Therefore, since the subject matter on which the rejection rests is not prior art, the rejection is not viable and should be withdrawn.

Reconsideration and allowance of all the pending claims are respectfully requested.

Should there be any matters that need to be resolved in the present application, the Examiner is respectfully requested to contact the undersigned at the telephone number listed below.

The Commissioner is hereby authorized in this, concurrent, and future replies, to charge payment or credit any overpayment to Deposit Account No. 25-0120 for any additional fees required under 37 C.F.R. §1.16 or under 37 C.F.R.§1.17.

Respectfully submitted,

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REL/mjr
November 30, 2004

APPENDIX:

The Appendix includes the following item(s):

1) Verified English-language translation of JP No. 2000-311045, filed October 11, 2000;

2) a copy of U.S. 60/222,734, filed August 3, 2000; and

3) a copy of U.S. 60/262,548.

08/03/00

Class	Subclass

ISSUE CLASSIFICATION

CTH
SB

PROVISIONAL APPLICATION NUMBER

Form PTO-1625
(Rev. 6/99)

(FACE)

FILE HISTORY

U.S. PATENT SERIAL NO. 60/222,734

VALENTI ET AL.

(cited on U.S. APPLICATION 2002/0041565)

PATENT APPLICATION SERIAL NO. ____________________

U.S. DEPARTMENT OF COMMERCE
PATENT AND TRADEMARK OFFICE
FEE RECORD SHEET

PTO-1556
(5/87)

*U.S. GPO: 1999-459-082/19144

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PATENT APPLICATION

60222734

60/222734

08/03/00

CONTENTS

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Bib Data Sheet

SERIAL NUMBER	FILING DATE	CLASS	GROUP ART UNIT	ATTORNEY DOCKET NO.
60/222,734	08/03/2000 RULE –	–	–	APP1286P-US

APPLICANTS

Craig F Valenti, Morristown, NJ ;
Kenneth Kerpez, Chester, NJ ;

** CONTINUING DATA *************************

** FOREIGN APPLICATIONS ********************

IF REQUIRED, FOREIGN FILING LICENSE GRANTED ** 11/08/2000 –

	STATE OR COUNTRY	SHEETS DRAWING	TOTAL CLAIMS	INDEPENDENT CLAIMS
Foreign Priority claimed ☐ yes ☐ no 35 USC 119 (a-d) conditions met ☐ yes ☐ no ☐ Met after Allowance Verified and Acknowledged ______ Examiner's Signature ______ Initials	NJ	4	–	–

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TITLE

Method and system for automated crosstalk identification and specrum management on multi-pair cables

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Docket Number:	APP 1286P-US

PROVISIONAL APPLICATION FOR PATENT COVER SHEET (Large Entity)

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53 (c).

JC541 U.S. PTO 60/222734 08/03/00

INVENTOR(S)/APPLICANT(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
Craig F.	Valenti	Morristown, NJ
Kenneth	Kerpez	Chester, NJ

☐ *Additional inventors are being named on page 2 attached hereto*

TITLE OF THE INVENTION (280 characters max)

Method and System for Automated Crosstalk Identification and Spectrum Management on Multi-Pair Cables

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ENCLOSED APPLICATION PARTS *(check all that apply)*

☒ Specification	*Number of Pages*	19	
☒ Drawing(s)	*Number of Sheets*	4	☐ Other (specify)

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT *(check one)*

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The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☒ No.

☐ Yes, the name of the U.S. Government agency and the Government contract number are: ____________

Respectfully submitted,

SIGNATURE William A. Schoneman   DATE August 3, 2000

TYPED or PRINTED NAME William A. Schoneman   REGISTRATION NO. *(if appropriate)* 38,047

TELEPHONE 973-829-3099

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P19LARGE/REV04

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Docket Number:	APP 1286P-US

PROVISIONAL APPLICATION FOR PATENT COVER SHEET (Large Entity)

INVENTOR(S)/APPLICANT(S)		
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I certify that this application and enclosed fee is being deposited on 8/3/2000 with the U.S. Postal Service "Express Mail Post Office to Addressee" service under 37 C.F.R. 1.10 and is addressed to the Assistant Commissioner for Patents, Washington, D.C. 20231.

Linda K. Adams

Signature of Person Mailing Correspondence

Linda K. Adams

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APP 1286P-US

UNITED STATES PROVISIONAL PATENT APPLICATION

OF

CRAIG F. VALENTI

AND

KENNETH KERPEZ

FOR

METHOD AND SYSTEM FOR AUTOMATED CROSSTALK IDENTIFICATION AND SPECTRUM MANAGEMENT ON MULTI-PAIR CABLES

METHOD AND SYSTEM FOR AUTOMATED CROSSTALK IDENTIFICATION AND SPECTRUM MANAGEMENT ON MULTI-PAIR CABLES

FIELD OF THE INVENTION

The present invention relates generally to the implementation and management of digital subscriber line (DSL) systems operating on copper twisted-pair telephone cables and, particularly, to an automated method and system for the prediction and/or identification of crosstalk between pairs within a cable and the spectrum management of such systems.

BACKGROUND OF THE INVENTION

The telecommunications industry has worked for over a decade to develop digital subscriber line (DSL), Integrated Services Digital Network (ISDN), high-bit-rate digital subscriber line (HDSL), asymmetrical digital subscriber line (ADSL) and other technologies to bring high speed data transfer to offices and homes without investing in new telecommunications infrastructure such as fiber optic lines. Network providers, however, must properly manage the introduction and application of such technologies to the existing local network.

An understanding of subscriber loop make-ups, including length, wire gauge and location of bridged taps, is key to the proper engineering of DSL systems. While some loop records exist, they may be inaccurate or out of date. Knowing the types of systems that are transmitting in a given cable is also critical, because of the resultant crosstalk and the potential need for spectrum management. Spectrum management is an engineering process that allows an operator to place new DSL systems into the plant in compliance with spectral compatibility guidelines and

standards, and to troubleshoot field problems suspected of being caused by crosstalk from other systems.

It would be desirable to have a technique that could identify and qualify all nonloaded subscriber loops in a mechanized and highly accurate manner without the need for special equipment or intervention at the subscriber's location.

Historically, local exchange carriers have carefully controlled systems that they place in the distribution network. T-carrier, used to support digital loop carrier remote terminals and private line services, is a highly engineered transmission system with carefully controlled power levels and pulse templates. ISDN Basic Rate Access and 2B1Q-based HDSL were carefully engineered for spectral compatibility assuming worst-case scenarios of long loops with bridged tap and high binder group fills. A similar philosophy was initially proposed for ADSL. DSL standards deliberations, however, were more vendor-driven, and more aggressive. In particular, the option to use a historically high transmit power level was allowed. Simulations show that, under certain conditions, such systems could result in spectral incompatibilities, wherein crosstalk from one type of system interferes with another type of system.

Several issues now complicate an operator's ability to deal with the situation. First, multiple technologies are being developed by equipment manufacturers, including DMT, CAP and QAM. Second, these systems run at multiple bit rates. Finally, and perhaps most importantly, the Telecommunications Act of 1996 includes loop unbundling provisions that make it possible for competing operators, often referred to as Competitive Local Exchange Carriers (CLECs), to gain access to individual loops. This activity was initially POTS-focused, but several operators are already offering ADSL-based unbundled services. Over time, the competitive local

environment may lead to several providers gaining access to the copper distribution plant, with each having a significant customer base. The customer base will be randomly dispersed in an area, driven by marketing forces and consumer choice. All this means that the spectral environment in a cable will be difficult to predict, and will be constantly changing.

It would be desirable to have a technique that could characterize the crosstalk environment on a loop-by-loop basis, in a mechanized and highly accurate manner without the need for special equipment or intervention at the subscriber's location. In the following section, the same system used to identify and qualify loops will be extended to support spectrum management.

There do exist mechanized systems, which are targeted at troubleshooting voiceband systems such as mechanized loop testing (MLT). There is also portable test equipment, e.g., DSL transmission impairment measurement test set (TIMS) on the market. Elastic Networks' EtherLoop DSL has a Spectrum Manager embedded in every transceiver, which purportedly identifies single disturber types. The algorithm that is used by Elastic Networks, however, cannot identify multiple crosstalk source types from a mixed crosstalk PSD, which is entirely new.

It is therefore an object of the present invention to overcome the deficiencies evident in the prior art in order to be able to take measurements in the DSL band and performing calculations with a centralized automated system to provide spectrum management.

It is a further object of the present invention to provide for coordination of DSL systems for case-by-case spectrum management, provisioning, or maintenance.

SUMMARY OF THE INVENTION

This invention provides automated assistance in deploying and managing digital subscriber line (DSL) systems, which operate on copper twisted-pair telephone cables and couple crosstalk into any other pair within the cable. Specifically, the invention is the ability to be able to predict or identify single and multiple disturbers from X-talk measurements, the specific algorithms for making these measurements, and a spectrum management system that uses the information for service provision, network maintenance, dispute resolution, etc.

The invention is a hardware and software system that measures the crosstalk spectral content on copper twisted-pairs, identifies the types of DSL systems, which are the sources for that crosstalk, and enables spectrum management. Measurements and crosstalk source identification are performed by the invention with automated algorithms without requiring a user to understand the details of the measurement methodology or identification algorithm. The crosstalk data is collected and used by a spectrum management system to enable more efficient spectrum management, DSL provisioning, and maintenance of the copper loop plant than is possible without such data.

Most solutions for qualifying a loop for DSL services do so without unveiling the exact make-up of the loop. A technique that can achieve precise loop make-up identification via single ended measurements is necessary. The availability of the exact make-up of the loops in the local plant will not only solve the problem of qualifying loops for DSL-based services, but will also support other important loop plant engineering functions.

The loop make-ups, and types and numbers of crosstalkers in a cable can be measured, recorded, and tracked. This database can be coordinated with a DSL provisioning system to allow

the highest possible service rates while ensuring spectral compatibility. Rather than using broad-brush loop estimates and spectrum management rules based on worst-case assumptions, precise loop make-ups and accurate noise characterization along with the actual powers of DSLs transmitting in the cable can be coordinated by the system.

This system is useful for network monitoring and maintenance. A DSL may experience significant degradation when signal to noise ratios (SNRs) are inadequate, perhaps when another source transmits a PSD that is too high. The system can isolate the causes of failures such as long loops or bridged taps, identify crosstalk sources, and help mitigate problems by techniques such as power back-off or lowering transmitted bit-rates. The system can also determine if an unbundled loop is receiving crosstalk levels that are within specifications.

Techniques for determining loop make-ups and for obtaining a spectrum analysis on a loop-by-loop basis are not the only methods for obtaining such information, but they have the advantage of being applied in a mechanized, single-ended fashion from the central office. Thus, a new "broadband test head" can be installed in the office that will automatically and routinely provide current information on loop make-ups and crosstalk. Using sophisticated signal processing and analysis approaches, we hope to be able to precisely determine loop make-ups for the entire nonloaded loop plant, including section lengths and bridged tap composition. The same approach can be used to gather and characterize crosstalk for each of the loops.

This information can be input to a provisioning and maintenance system that will retain and correlate the records. This database can in turn be used for a number of important functions, such as loop plant engineering, loop qualification and provisioning of DSL-based services, spectrum management, and maintenance of the loop plant. We believe that such a capability is

required to fully exploit the power of emerging DSL technologies, and to effectively deal with the increasingly complex and dynamic unregulated local loop environment.

DESCRIPTION OF THE DRAWINGS

Figure 1 is a diagram of a time division reflectometer (TDR) trace for a 12 kft AWG24 with a 1kft bridged tap located at 1 kft and 10 kft.

Figure 2 is a diagram of a time division reflectometer (TDR) trace for 3 kft AWG26 cable spliced to a 12 kft AWG24 cable.

Figure 3 is a diagrammatic depiction of crosstalk, transmitted signal coupling and received crosstalk.

Figure 4 is a diagram of a spectrum management system according to the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

The approach used for determining the loop make-up is in the time-domain. Special probing pulses are launched onto the loop via the local metallic test bus. If a discontinuity is present (gauge change, bridged tap, end of loop), a signal (echo) travels back to the CO corresponding to the discontinuity. Such echoes are collected in the CO and are then processed. The solution employs a combination of advanced reflectometry and signal processing techniques. The advanced reflectometry allows the detection of very weak echoes generated at the ends of long loops, while additional signal processing is necessary to resolve overlapping echoes and identify discontinuities.

Several problems have to be solved in order to achieve the capability of exact loop make-up identification, especially those related to the limitations of current Time Domain Reflectometers (TDRs). First of all, today's TDRs have an effective range of some number of kilofeet (kft) and are not sufficient to allow detection of echoes generated by far discontinuities. Secondly, today no commercial TDR has the capability of detecting echoes generated by gauge changes. Moreover, even when all echoes can be detected it is not trivial to resolve them. In fact, the available observations consist of an unknown number of echoes, some overlapping in time and frequency, some not, some *real* and some *spurious*, that exhibit unknown amplitude, unknown time of arrival and unknown shape. The problem of resolving the above observations on the basis of a *single-sensor experiment* is a very complex problem that is seldom addressed in the literature.

An example of a TDR trace is given in Fig. 1, for the case of a 12 kft AWG24 gauge cable with a 1 kft bridged tap located either at 1 kft (Case A) or at 10 kft (Case B). The typical negative-positive sequence characterizing a bridged tap is manifest for Case A, but not for Case B where there is no sign of the presence of an echo. However, by using special signal processing on the waveform of Case B, it is now possible to see the negative positive echoes of the bridged tap (Case B + Processing).

With the use of special signal processing techniques, it is also possible to see gauge changes. The fact is that the echoes generated by a gauge change cannot normally be seen, not because they are too weak to be detected, but because they are hidden. An example is given in Fig. 2, where the TDR trace of a 3 kft AWG26 cable spliced to a 12 kft AWG24 cable is shown. The normal trace of a TDR does not reveal the presence of any echo, but the processed trace

clearly shows a negative echo that indicates the transition from a medium with higher characteristic impedance to a medium with a lower one.

Finally, very good results have been obtained with an algorithm that uses sophisticated signal processing to perform loop make-up identification. Preliminary tests indicate that the algorithm is able to precisely identify loop make-ups, whatever topology they may have

Spectral compatibility is the property whereby crosstalk among different systems transmitting on different pairs in the same twisted-pair cable does not cause significant degradation to the performance of any of the systems.

Spectrum management is the process of deploying DSLs in the loop plant in a manner that ensures spectral compatibility. Figure 3 depicts crosstalk in a typical loop environment, including near-end crosstalk (NEXT) and far-end crosstalk (FEXT). Current techniques for spectrum management apply relatively rigid rules uniformly across the entire loop plant, as embodied in the draft spectrum management standard currently under development by ANSI committee T1E1.4. These rules do not take into account the individual types of crosstalk sources or crosstalk couplings related to a particular pair in a cable, which may be considerably different than the near worst-case couplings that are assumed in the draft standard. Thus, a system that can characterize crosstalk on a loop-by-loop basis has the potential to yield a much more granular crosstalk characterization of the plant. This data, entered into a new loop spectrum management database, in turn has the potential to be mined, correlated and exploited to provide more optimal performances for individual subscriber loops.

To see how such a database might be created, we give the following example in which the crosstalk noise on a given pair is analyzed and characterized. NEXT from an upstream ADSL

source is measured for a number of pair-to-pair combinations. These NEXT PSDs are correlated with the PSD crosstalk templates of some known sources. As can be seen from the calculated results in Table 1, each measured NEXT is highly correlated with the template NEXT from upstream ADSL. The unknown NEXT source is correctly identified.

Table 1. Correlations of measured NEXT from unknown source with known crosstalk templates

Measured NEXT	BRI NEXT	HDSL NEXT	T1 NEXT	ADSL Down NEXT	ADSL Up NEXT
5 -> 4	0.218	0.790	-0.276	-0.221	0.975
6 -> 15	0.194	0.798	-0.269	-0.215	0.992
11 -> 20	0.183	0.792	-0.269	-0.214	0.957
10 -> 21	0.153	0.808	-0.258	-0.204	0.994
4 -> 25	0.201	0.784	-0.267	-0.214	0.983
3 -> 12	0.071	0.768	-0.223	-0.174	0.938
13 -> 15	0.088	0.770	-0.227	-0.179	0.952
9 -> 20	0.230	0.791	-0.279	-0.223	0.962
14 -> 24	0.213	0.806	-0.276	-0.220	0.983
8 -> 18	0.120	0.802	-0.246	-0.194	0.976
2 -> 22	0.106	0.771	-0.233	-0.184	0.969
12 -> 4	0.085	0.735	-0.216	-0.171	0.935
1 -> 5	0.130	0.798	-0.247	-0.195	0.975
7 -> 18	0.066	0.790	-0.231	-0.177	0.896

Let us consider a system that analyzes the responses of subscriber loops to probing signals to perform loop identification, and measures crosstalk and identifies the types of systems that are the sources for that crosstalk. The data is collected and used by a provisioning and maintenance system to enable more efficient engineering, provisioning, spectrum management, and maintenance of the copper loop plant.

If a DSL or other system transmits a power spectral density (PSD) on one pair of a multi-pair cable, then this PSD is multiplied by a crosstalk coupling function in the frequency domain, and the resulting crosstalk couples into a nearby pair. Spectral compatibility is the property that crosstalk between different systems that transmit in the same twisted-pair cable does not cause significant degradation to the performance of any of the systems. Spectrum management is the process of deploying DSLs in the loop plant in such a manner that ensures spectral compatibility. Current techniques for spectrum management apply rigid rules uniformly across the entire loop plant, as embodied in the draft spectrum management standard currently under development by ANSI-accredited DSL access standards committee T1E1.4. These rules do not take into account the individual types of crosstalk sources and crosstalk couplings of a particular cable, which may be considerably different than the near worst-case couplings that are assumed in the draft spectrum management standard. In particular, these rules take a worst case approach based on the belief that measurement and identification of X–talk sources, and subsequent spectrum management, is an intractable, if not impossible, problem.

As previously mentioned the present system has the ability to identify the source of a disturber from a cross–talk measurement. The system measures the cross–talk on a cable pair and from that measurement identifies the source of the cross–talk. Once the source is identified

the information may be used to populate a database that can be used for spectrum management, including but limited to dispute resolution, service capability, maintenance, etc.

With reference to Fig. 4, the invention comprises three functional elements:

1. Algorithms for identifying disturbers from x–talk measurements;

2. A cross–talk measurement device.

3. A spectrum management system that inputs measurements from a number of the devices that measure the crosstalk. The spectrum management system may also run the above algorithm or the crosstalk measurement devices may also run the algorithm

The invention measures the crosstalk on an individual basis. The measurements can identify pairs with crosstalk couplings that are well below near worst-case couplings, and systems on these pairs may transmit at higher bit rates or over longer distances than current practice allows. Rather than use broad-brush spectrum management rules based on worst-case assumptions, the transmitted bit rates and powers of a number of DSLs transmitting in the same cable can be coordinated by the spectrum management system which receives multiple crosstalk measurements and processes them. The types and numbers of crosstalkers in a cable, or in an individual cable binder, can be measured, recorded, and tracked. The invention can be coordinated with a DSL provisioning system to allow the highest possible service rates to be provisioned while ensuring spectral compatibility. The invention can greatly increase the number of customers that can be served by DSL and the bit rates that they can receive.

The spectrum management system could be connected to many Digital Subscriber Line Access Multiplexers (DSLAMs) belonging to different carriers sharing an unbundled loop plant. As such the invention could enable all the users of the unbundled telephone plant to provide higher service levels than if they provisioned services in the uncoordinated fashion that is current practice. Disputes between different service providers, or between CLECs leasing loops and the ILECs who lease them, can be quickly and unambiguously resolved.

The invention is useful for network monitoring and maintenance. A DSL may experience significant degradation because crosstalk couplings are too high or because another DSL is sending a power spectral density (PSD) that is too high. The invention can isolate the causes of failures such as high bit error rates, identify crosstalk sources, and help mitigate problems by techniques such as power back-off or lowering transmitted bit-rates. The invention identifies what type of DSL is causing a problem. The spectrum management system could then perform a query or use its records to determine the exact transmitter and pair that are causing the problem. Solutions such as using a different pair could be recommended or solutions such as lowering the crosstalker's PSD could even be implemented automatically. For example, when DSL #1 experiences a service outage, the invention determines what type of system generated the crosstalk that caused the outage. Then the spectrum management system identifies the crosstalker DSL #2 as one of this type of systems that recently turned on, and lowers the transmitted PSD and/or bit rate of DSL #2 until DSL #1 can function normally. A similar process is to coordinate many DSLs to provide joint optimality.

The devices that measure crosstalk received on a twisted pair could be embodied in several ways. A broadband test head (BBTH) can access the loop through metallic test and

directly measure received crosstalk. The BBTH could excite a pair with a signal and measure the received signal on another pair to measure the crosstalk coupling. Alternatively, the crosstalk coupling could be reconstructed from the received crosstalk. This is done by first estimating or determining from records what the transmit PSD of the crosstalker is, and then using the combination of the estimated transmit PSD and the received crosstalk PSD to estimate the crosstalk coupling. Such estimation can be done by the invention with a number of simultaneous crosstalkers. The user does not need to know the details of the measurement and estimation procedure. Another embodiment of a device that measures crosstalk could be the receiver of an existing DSL modem. The purpose of a receiver is to estimate the transmit signal form a received signal plus noise, and in so doing it essentially estimates the received crosstalk noise at each sample. Moreover, a typical DSL system combines a number of DSL modems into a DSLAM at a central office, and the signal and received crosstalk noise is typically available as data such as bit and gain tables through a system that is proprietary to a DSLAM vendor. All that is needed are communications links that can carry this information from the DSLAM to the spectrum management system.

The present invention identifies the sources of crosstalk. This can be performed in the devices that measure crosstalk, or in the spectrum management system, or jointly in both. Crosstalk identification incorporates a number of models of DSL transmission systems and cable parameters into a computer calculation of DSL system identification. The calculation is performed with certain defined parameters such as reference crosstalk templates, DSL power spectral densities and crosstalk coupling data. This invention can identify mixed crosstalk types,

i.e., the crosstalk sources are more than one type of DSL system. The spectrum management system operates in the following modes:

1. Line-by-line. The noise on a particular telephone loop is measured and analyzed by the invention to determine the crosstalk sources and their coupling. The spectrum management system uses this information to provision spectrally compatible DSL, or to trouble-shoot, on this line. It could determine if the crosstalk coupling is too high or if the transmitted PSD level of the crosstalk source is too high.

2. Coordinated across multiple pairs that one service provider uses. Items in 1. plus coordinated spectrum management to jointly optimize DSL provisioning and jointly trouble-shoot problems on all pairs that connect to the service provider's spectrum management system. Also, the crosstalk identification can be performed jointly using the measurements from multiple pairs and possibly by accessing loop databases.

3. Coordinated across multiple service providers. Items in 1. and 2. plus coordinated DSL provisioning and troubleshooting across all carriers. This mode could be incorporated into rules for loop unbundling, and the spectrum management system could police those rules

The spectrum management system could be part of, or link to, a DSL provisioning or loop qualification system, and it can use the records and database of such a system to augment its accuracy. The spectrum management system could record measurements of crosstalk at different time intervals. These measurements could identify usage patterns of different DSLs over time and tailor the other DSLs to exploit periods of low crosstalk; allowing active users to transmit

higher bit rates when other users are inactive. It could identify bursting or short-term stationary crosstalk.

Although the invention is specified for digital subscriber lines (DSL), it could be used for any types of transmission systems operating on multi-pair metallic cables that are not specifically called DSLs. The invention could be applied to campus networks or private LANs linked by twisted pairs. The invention could be combined with a system that automatically calculates loop make-ups. The invention could be part of a larger system or OSS.

CLAIMS

We claim:

1. A system for automated spectrum management on a network having a plurality of multi-pair cables comprising:

   a cross–talk measurement device for measuring crosstalk between said plurality of multi-pair cables;

   a crosstalk identification device for identifying the source of the crosstalk on said plurality of multi-pair cables using said crosstalk measurement;

   a database of crosstalk measurements and sources wherein said database is used for spectrum management.

2. A method for automated spectrum management on a network comprising a plurality multi-pair cables comprising the steps of:

   measuring crosstalk between said plurality of multi-pair cables;

   identifying the source of the crosstalk on said plurality of multi-pair cables using said crosstalk measurement;

   collecting a plurality of crosstalk measurements and sources of crosstalk wherein said database is used for spectrum management.

3. An apparatus for the automatic identification of a source of crosstalk between multi-pair cables in a network having a plurality of multi-pair cables comprising:

means for measuring crosstalk between said multi-pair cables;

means for identifying the source of said crosstalk using said measurement.

4. A method for the automatic identification of a source of crosstalk between multi-pair cables in a network having a plurality of multi-pair cables comprising:

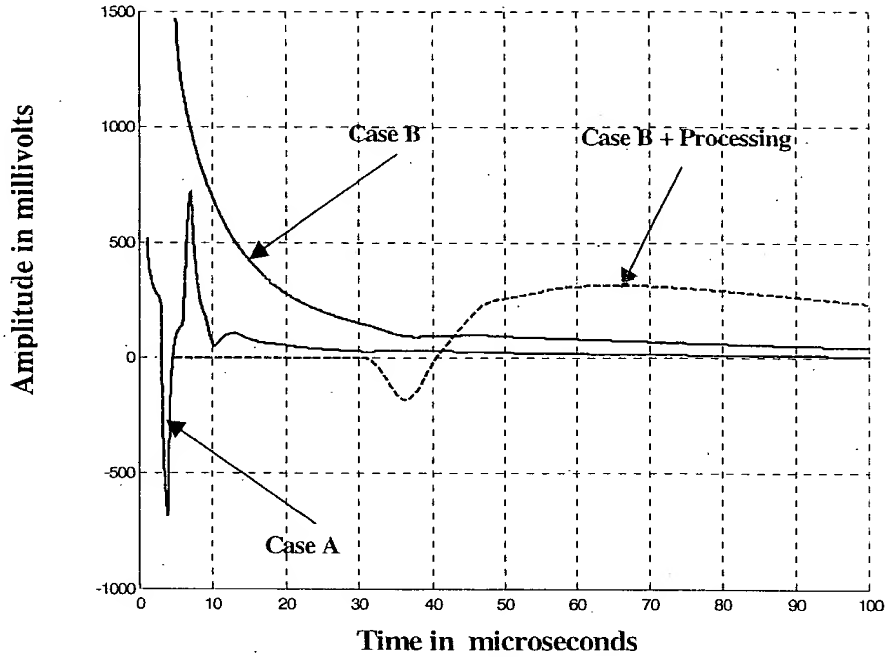
measuring the crosstalk between said multi-pair cables;

transferring said measurement to a central processing unit;

identifying the source of said crosstalk using said measurement by analyzing said measurement in said central processing unit.

ABSTRACT

This invention provides automated assistance in deploying and managing digital subscriber line (DSL) systems, which operate on copper twisted-pair telephone cables and couple crosstalk into any other pair within the cable. Specifically, the invention is the ability to be able to predict or identify single and multiple disturbers from X-talk measurements, the algorithms for making these measurements, and a spectrum management system that uses the information for service provision, network maintenance and dispute resolution.


Amplitude in millivolts
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1000
500
0
-500
-1000
Case B
Case B + Processing
Case A
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10
20
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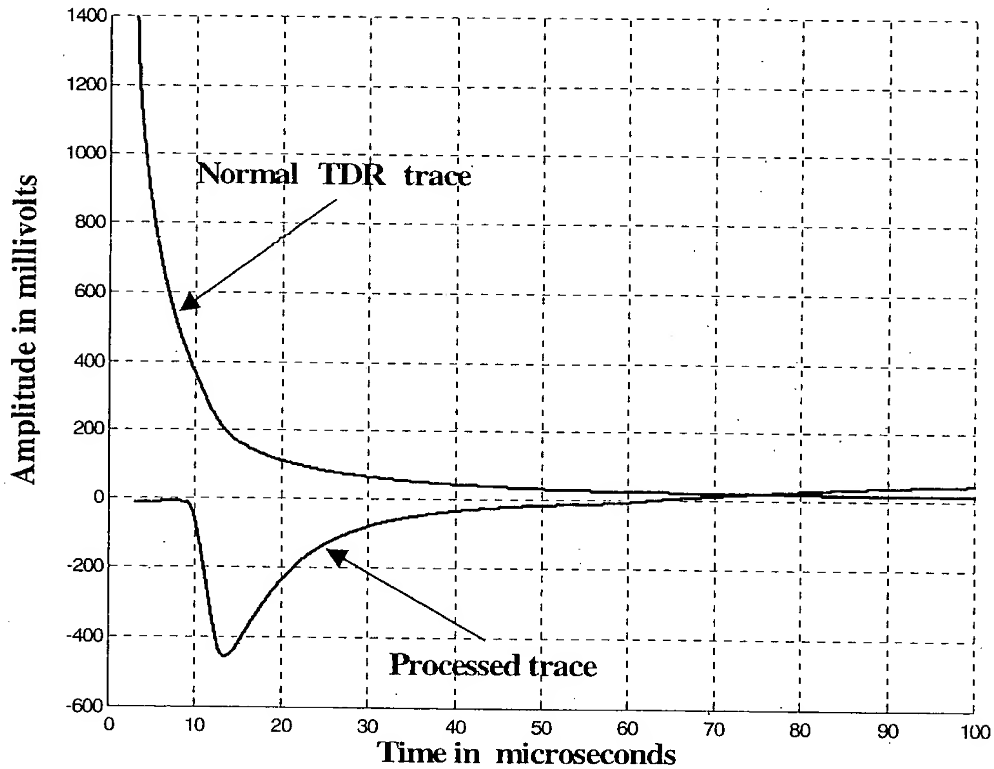
100
Time in microseconds

Figure 1


Amplitude in millivolts
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-200
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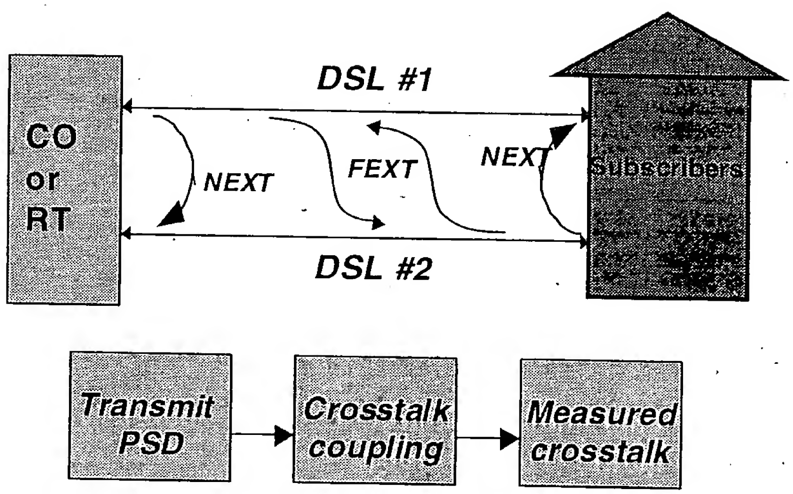
Time in microseconds

Fig. 2

FIG. 3


DSL #1
CO
or
RT
NEXT
FEXT
NEXT
Subscribers
DSL #2
Transmit
PSD
Crosstalk
coupling
Measured
crosstalk

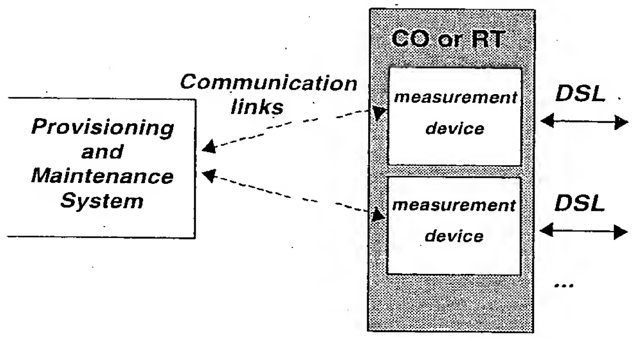

CO or RT
Communication links
Provisioning and Maintenance System
measurement device
measurement device
DSL
DSL
...

Figure 4

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United States Patent Application Publication No. 2002/0041565, page, ________ line ________,

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FILE HISTORY

U.S. PATENT SERIAL NO. 60/262,548

VALENTI ET AL.

(cited on U.S. APPLICATION 2002/0041565)

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01/17/01

Class	Subclass

ISSUE CLASSIFICATION

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PROVISIONAL APPLICATION NUMBER

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J6929 U.S. PTO
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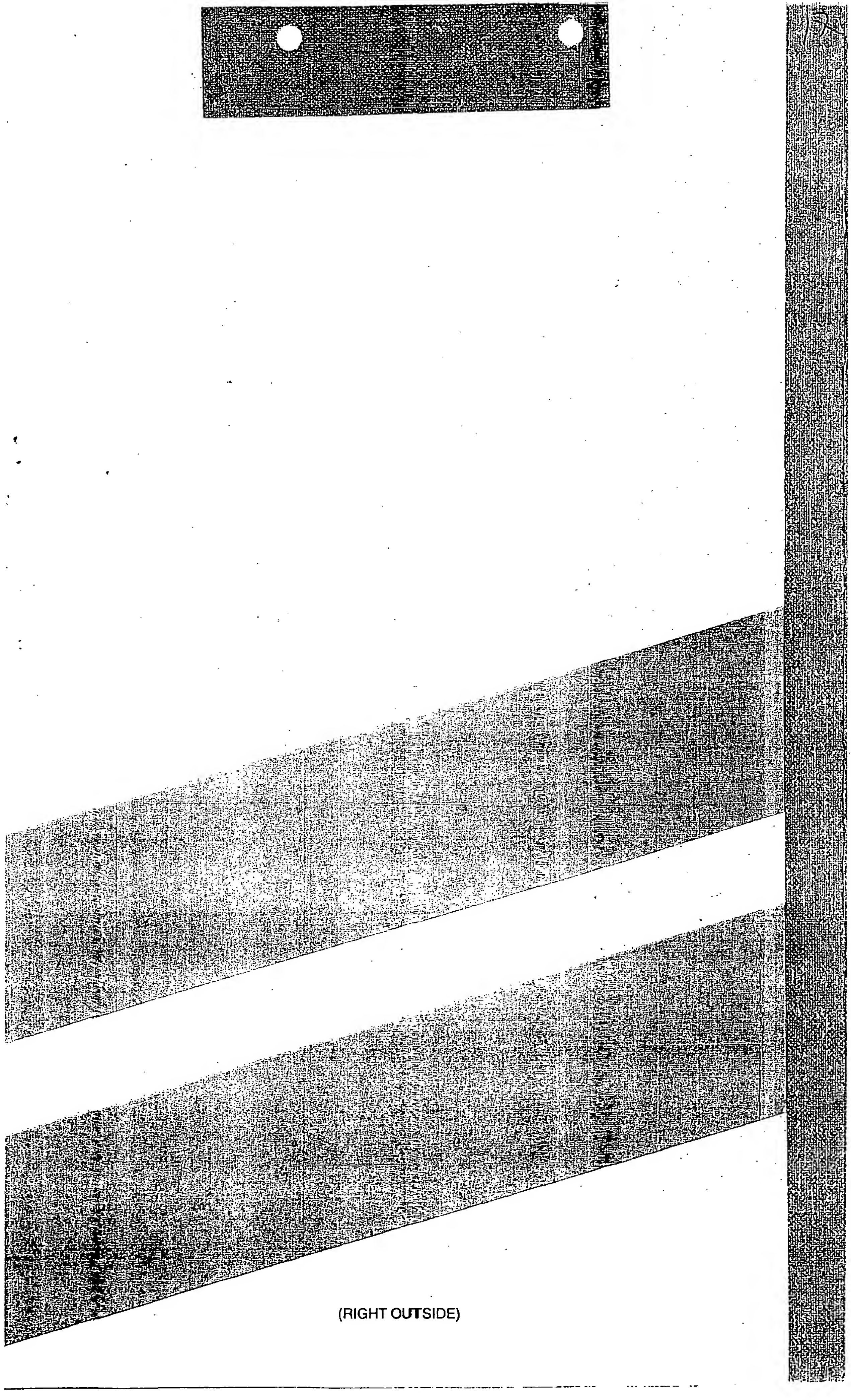

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PTO-1556
(5/87)

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APPLICANTS

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Craig Valenti, Morristown, NJ;
Kenneth J. Kerpez, Long Valley, NJ;

** CONTINUING DATA *************************

** FOREIGN APPLICATIONS ********************

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Foreign Priority claimed ☐ yes ☐ no 35 USC 119 (a-d) conditions met ☐ yes ☐ no ☐ Met after Allowance Verified and Acknowledged ____ Examiner's Signature ____ Initials	STATE OR COUNTRY	SHEETS DRAWING	TOTAL CLAIMS	INDEPENDENT CLAIMS
	NJ	10		

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TITLE

Fequency-domain approach to crosswalk identification and cancellation in digital subscriber line systems

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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

JC929 U.S. PTO 60/262548 01/17/01

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Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
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Craig	Valenti	Morristown, New Jersey
Kenneth J.	Kerpez	Long Valley, New Jersey

☐ *Additional inventors are being named on the ____ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (280 characters max)

Frequency-Domain Approach To Crosstalk Identification and Cancellation In Digital Subscriber Line Systems

Direct all correspondence to: **CORRESPONDENCE ADDRESS**

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City	Morristown	State	New Jersey	ZIP	07960
Country	US	Telephone	973-829-3099	Fax	973-829-2366

ENCLOSED APPLICATION PARTS *(check all that apply)*

☒ Specification *Number of Pages* 30

☒ Drawing(s) *Number of Sheets* 10

☐ Application Data Sheet. See 37 CFR 1.76

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Respectfully submitted,

SIGNATURE [signature]

Date 01/17/2001

TYPED or PRINTED NAME William A. Schoneman

REGISTRATION NO. 38,047
(if appropriate)

Docket Number: APP 1379-US

TELEPHONE (973) 829 - 3099

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CERTIFICATE OF MAILI BY "EXPRESS MAIL" (37 CFR .) Applicant(s): **Stefano Galli, Craig Valenti and Kenneth J. Kerpez**			Docket No. **APP 1379-US**
Serial No.	Filing Date	Examiner	Group Art Unit

Invention:

FREQUENCY-DOMAIN APPROACH TO CROSSTALK IDENTIFICATION AND CANCELLATION IN DIGITAL SUBSCRIBER LINE SYSTEMS

JC929 U.S. PTO 60/262548 01/17/01

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UNITED STATES PROVISIONAL PATENT APPLICATION

OF

STEFANO GALLI

CRAIG VALENTI

KENNETH J. KERPEZ

FOR

FREQUENCY-DOMAIN APPROACH TO CROSSTALK IDENTIFICATION AND CANCELLATION IN DIGITAL SUBSCRIBER LINE SYSTEMS

FREQUENCY-DOMAIN APPROACH TO CROSSTALK IDENTIFICATION AND CANCELLATION IN DIGITAL SUBSCRIBER LINE SYSTEMS

FIELD OF THE INVENTION

The present invention relates generally to Digital Subscriber Line ("DSL") technology and more particularly to how DSL exploits the existing, ubiquitous, copper telephone loop plant to provide megabit per second (Mbps) high-speed Internet access and other services.

BACKGROUND OF THE INVENTION

Appendix A is hereby incorporated by reference.

SUMMARY OF THE INVENTION

Appendix A is hereby incorporated by reference.

BRIEF DESCRIPTION OF THE DRAWINGS

Appendix A is hereby incorporated by reference.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Appendix A is hereby incorporated by reference.

CLAIMS

What is claimed is:

1. Types of DSL generating crosstalk in accordance with the description in Appendix A.

2. A method comprising steps in accordance with the description in Appendix A.

3. A system comprising elements in accordance with the description in Appendix A.

ABSTRACT

Crosstalk between multiple services transmitting through the same telephone cable is the primary limitation to digital subscriber line services. Methods for estimating crosstalk sources and crosstalk couplings, as well as methods of exploiting these estimates in crosstalk cancellation are discussed. The crosstalk sources are identified in the frequency domain by maximizing the correlation with a "basis set" of received crosstalk PSDs which consist of the cascade of a finite set of known transmit PSDs types times a representative set of crosstalk couplings. Multiple crosstalk types are identified with a technique of successive spectral subtraction. The crosstalk estimates are quantized, and are used to determine an optimal set of weightings for a novel type of predictive filtering that minimizes the received crosstalk power.

APPENDIX A

1. Introduction

Digital Subscriber Line (DSL) technology exploits the existing, ubiquitous, copper telephone loop plant to provide megabit per second (Mbps) high-speed Internet access and other services. For each subscriber, telephone and DSL signals travel on a single twisted pair from a central office (CO) to the subscriber. Many, sometimes thousands, of twisted pairs are wrapped together in a single cable. The twisting of the pairs keeps the average amount of electromagnetic coupling between the balanced circuits on each pair to a low level, resulting in low crosstalk coupling between circuits. Twisted-pair cabling was invented by Alexander Graham Bell, and was probably his greatest invention other than the telephone itself, allowing service to all locations without using the prohibitive amount of space that open wire would have required.

Telephone loops were designed and built to carry voice services, requiring only a very low probability of intelligible crosstalk at voice frequencies, up to a few kHz. Crosstalk generally increases with increasing frequency [1], and since DSL frequencies extend into MHz, crosstalk becomes the major limitation to high-speed DSL. A number of individual twisted pairs are wrapped together in a binder, and a number of binders are in each telephone cable. There are typically 12, 13, 25, 50 or 100 pairs in a binder, and the crosstalk between pairs in the same binder is much higher than it is between different binders. Telephone cabling can be thought of as a multi-input, multi-output interference channel [1] with crosstalk between 12 to 100 channels [2], although there are typically a smaller number of high-power crosstalkers into each pair.

DSL technology is still fairly new. The current approach is to treat each signal on each twisted pair entirely separately, and to assume that crosstalk is simply additive Gaussian noise of which nothing is known. With this approach, subscribers can enjoy relatively high speed service, far faster than voiceband modems, up to multiple Megabits per second (Mbps). This is the

current static approach to DSL spectrum management [3], which is a fixed set of engineering rules to ensure that crosstalk is not overly harmful.

As time progresses it is expected that there will be many more DSL users, and that they will demand higher speed service. This will result in more crosstalk, and higher-bandwidth services that are more vulnerable to crosstalk. The twisted-pair cable can be considered a multiuser channel by expressing the received signal vector as

$$Y(f) = R(f) + N(f) + H(f)D(f) \tag{1.1}$$

where $R(f)$ is the received message vector, $N(f)$ is the vector of independent background noise, $D(f)$ is the vector of transmitted signals creating crosstalk on nearby pairs, and $H(f)$ is the matrix of crosstalk couplings. In the case of near-end crosstalk (NEXT), $R(f)$ is transmitted on one end of the cable and $D(f)$ is transmitted on the other end. The received crosstalk $H(f)D(f)$ can be canceled, minimized or otherwise treated to be less interfering than pure noise. Dynamic spectrum management becomes possible. The idea of treating a telephone cable as a multiuser channel is not new, and some very good theoretical work in this area was performed in years past [4]. However, the subject has only recently become practical, and interest is now increasing [5-9]. Much current interest is in harnessing the time-domain equivalent of these equations, including sequences and pulse arrival times, in multiuser transceiver structures. Multiuser techniques for wireless systems have been finely honed to improve wireless capacity, and perhaps it is now time to apply these techniques to improve the capacity of wireline services.

Unlike mobile wireless, the twisted-pair multiuser channel is generally time invariant. Crosstalk couplings may vary as the temperature of the cable changes, but only very slightly. The crosstalk sources may turn on and off, but not very often since the main application is "always on" Internet access. Time invariance allows the possibility of very accurate estimates of

crosstalk coupling using large sample sizes. Joint statistics can be obtained by a "third-party", which is connected to all lines through communications links to the modems, and the knowledge of all the transmitted data could be used to estimate the crosstalk couplings. Received crosstalk could even be measured by temporarily connecting measurement equipment to a single pair, and crosstalk couplings could be measured by connecting measurement equipment to multiple pairs. The accuracy of estimates depends strongly on which elements of the multi-pair cable may be accessed, for example crosstalk couplings can be estimated accurately by accessing data from both transmitters and receivers. A thorny issue is gaining access to all the loops, or modem data, of different service providers who are sharing a cable in today's unbundled loop plant. Crosstalk parameter estimation can be performed off-line using very many samples of data. While knowledge of crosstalk parameters can be useful on their own for spectrum management and maintenance purposes, it can also be used at run time to enhance modem performance. Table 1 presents differences between long-term, off-line, crosstalk parameter estimation and run-time usage. The table is approximate; techniques from either column could be combined or interchanged.

Current techniques for DSL spectrum management assume static worst case crosstalk types and crosstalk couplings. Dynamic spectrum management would take into account the individual types of crosstalk sources and crosstalk couplings of each particular cable, and could greatly increase the number of customers that can be provided DSL service and their bit rates. The "Operational" row of Table 1 is generally beyond the scope of this paper but it may have great practical interest. There are many vagaries in the telephone outside plant, some older cables have poor crosstalk performance, etc. Unanticipated problems from crosstalk are likely to occur, and may be extremely difficult to diagnose. A "third-party" or operations center that could gain

access to multiuser crosstalk statistics would be far more capable of diagnosing crosstalk problems than an uninformed technician. Solutions such as power back-off could even be implemented at the operations center, and these processes could be automated.

This paper focuses on a particular schema for crosstalk identification in the frequency domain, which may be used for subsequent cancellation. This schema is relatively easy to implement because it can be performed in any single receiver. First an individual receiver estimates which varieties of DSL are generating crosstalk. This can be accomplished because there is actually a small number of common crosstalker types at high frequencies: T1 lines, integrated services digital subscriber lines (ISDN), high bit-rate digital subscriber lines (HDSL), single-pair high bit-rate digital subscriber lines (HDSL2), asymmetric digital subscriber lines (ADSL), and symmetric digital subscriber lines (SDSL) (soon G.shdsl and very-high rate digital subscriber lines (VDSL) will be added to this list). Each of these crosstalker types transmits a unique power spectral density (PSD), and this PSD is estimated with classic matched-filter correlation techniques. Thus, the transmitted PSD is non-linearly estimated by quantizing it to equal one of the known types, eliminating much ambiguity. This identification algorithm is described in Section 3, and is extended to the case of multiple crosstalkers by a process of successive estimation and cancellation using spectral subtraction.

Knowledge of the type of crosstalkers may be used for crosstalk cancellation in a DSL receiver. Once the type of the crosstalk source is determined, then the correlations of the source of the crosstalk are known, assuming correct decisions. These correlations are used in this paper to construct a an optimal set of weightings for a type of predictive filtering that minimizes the received crosstalk power before detection in the receiver. The coefficients of the predictive filter

are predetermined based on the known properties of each of the types of crosstalk. This crosstalk cancellation methodology is described in Section 4.

The next section of this paper reviews the major issues concerning crosstalk and its identification. Conclusions are drawn in the last Section of this paper.

2. Crosstalk Characterization

Sources of crosstalk are often called "disturbers." There are two types of crosstalk: near-end crosstalk (NEXT) and far-end crosstalk (FEXT). NEXT is more powerful than FEXT, particularly below about 1 MHz where many DSLs use overlapping spectra. If there is one crosstalker, then the received crosstalk PSD is the product of a PSD transmitted on a nearby pair times the crosstalk coupling PSD. With multiple crosstalkers the received crosstalk PSD is the linear sum of each component.

Traditionally, the telecommunications industry has characterized crosstalk in terms of power sums. For a given pair in a binder group, the power-sum NEXT is formed from the sum of the pair-to-pair NEXT coupling powers of the other pairs in the binder group to this given pair. For a typical 25-pair binder group, the 25 power sums are shown in Figure 2. Two things should be noted here. The first is that the power sum is usually displayed as a power sum "loss", and the lower the loss the higher the NEXT coupling. The second is that the NEXT power-sum loss is approximately linear with frequency on the log-log scale. The NEXT model often used for studies in industry forums is stated as expected 1% worst case power sum crosstalk loss as a function of frequency. This means that on average, 1% of the pairs tested are subjected to power-sum crosstalk loss worse (less) than assumed by the model at the given frequency. Such a model is a smooth curve versus frequency, in which the loss decreases at about 15 dB per decade of frequency. The statistical model ensures that the 1% worst case NEXT power sum level

follows the curve over frequency but this noise level may appear on different pairs at different frequencies. The 24-disturber NEXT power level for one specific pair is not a smooth curve if plotted over frequency and the deviation from the statistical model increases as the number of interferers used in the power sum is reduced. The power-sum loss for less than a full binder group depends on the distribution of the pairs on which the crosstalking signal appears.

Of most interest to the work presented here are the individual pair-to-pair NEXT couplings. For a 25-pair binder group there are 300 distinct pair-to-pair couplings (assuming symmetry). Examples of actual pair-to-pair NEXT couplings are given in Figure 3. It should be noted that there is wide variation of coupling strength for each pair-to-pair combination with frequency. The power summing process smoothes and averages some of this variation.

The received signal on pair number k can be expressed as

$$Y_k(f) = R_k(f) + N_k(f) + \sum_{i=1, i\neq k}^{N} H_{ik}(f) D_i(f) \tag{2.1}$$

where $R_k(f)$ is the received message signal, $N_k(f)$ is independent background noise, $D_i(f)$ is the signal transmitted on pair i, $H_{ik}(f)$ is the crosstalk coupling between pair i and pair k, and the crosstalk received on pair k from a system transmitting on pair i is $H_{ik}(f)D_i(f)$. Crosstalk has a number of elements which may be identified or estimated: the crosstalk coupling $H_{ik}(f)$ between each pair, the crosstalkers' transmitted spectrum $D_i(f)$, sequences of sampled received crosstalk, etc. DSL modems can measure crosstalk samples. Assuming correct decisions, the received sampled sum of crosstalk and noise is easily obtained in each receiver by subtracting $R_k(f) = \hat{R}_k(f)$ from $Y_k(f)$. These samples and their statistics can be exploited to improve the performance of the receiver, much like wireless multiuser detectors. Often a process of successive estimation and cancellation is performed where the most powerful crosstalk interferer is first estimated and subtracted, then the next most powerful, etc.

3. Crosstalk Identification in the Frequency Domain

When crosstalk is measured while a DSL system is running, what is measured or estimated is the crosstalk in the bandwidth of the considered DSL system. For this reason, other DSL services running on adjacent pairs may not be detected if their bandwidth is not significantly overlapping, with the bandwidth of the disturbed system. A typical example would be ISDN crosstalk into non-overlapped downstream ADSL. If this is the case, there is certainly no performance degradation for the considered DSL service but, from a spectrum management point of view, it may be important to have an accurate map of all the services that generate crosstalk into a given pair. Moreover, it may also be important to identify the services that are generating crosstalk on a pair that may not even be carrying DSL services. It is worth pointing out that an accurate map of all the services that generate crosstalk into a given pair is an impossible task to achieve via modem-based methods of system identification if the considered pair is not in use. The only way to achieve such a complete description of the crosstalkers regardless of the availability of a sequence of observations, is to perform a preliminary PSD measurement, e.g. via a spectrum analyzer or a selective voltage meter. In the following sub-sections, we will show how crosstalk identification may be achieved on the basis of this preliminary PSD measurement. We propose a novel method for crosstalk identification in the frequency domain by computing the correlation coefficient between the measured spectrum and a set of pre-defined PSDs that may be viewed as a crosstalk "basis set".

At the heart of the crosstalk identification algorithm is a calculation of crosstalk correlation in the frequency domain. The correlation receiver is known to be an optimum detector in the case of equally likely transmitted signals with known waveforms transmitted over an AWGN channel. It is mathematically equivalent to the matched-filter receiver which can be

shown to maximize the output signal to noise ratio by using Schwarz's inequality [10]. The basic structure of a correlation receiver is used here, except that it is adapted to our case with known transmitted signals but unknown crosstalk couplings

The correlation coefficient $\rho_{X,Y}$ between two data arrays $X = \{x_1,...., x_N\}$ and $Y = \{y_1,...., y_N\}$ with standard deviations σ_X and σ_Y and means μ_X and μ_Y, is defined as

$$\rho_{X,Y} = \frac{Cov(X,Y)}{\sigma_X \bullet \sigma_Y} \quad ,$$

where $Cov(X,Y) = \frac{1}{N}\sum_{j=1}^{N}(x_j - \mu_X) \bullet (y_j - \mu_Y)$ and $-1 \le \rho_{XY} \le 1$.

The correlation coefficient is a measure of how well the two data sets move together (positive values) or move apart from one another (negative values).

For our purposes the data array $Y = \{y_1,...., y_N\}$ is the measured crosstalk power spectrum density (PSD) of the unknown DSL disturber. The data array $X = \{x_1,...., x_N\}$ is a reference or basis crosstalk PSD profile caused by a known DSL disturber. Each basis set of crosstalk PSDs is generated from a single canonical set of measured strong pair-to-pair crosstalk couplings and a specific type of transmitted DSL PSD. Each type of DSL transmitted PSD is multiplied by all of the canonical crosstalk couplings to generate a basis set for that DSL. The supposition is that a member of this basis crosstalk set is highly correlated with any crosstalk that is strong enough to be troublesome or measurable. The canonical set of pair-to-pair couplings is shown in Figure 4. The canonical set chosen for this study comprises the fourteen out of 300 possible pair-to-pair NEXT couplings with the smallest crosstalk loss sum. The crosstalk loss sum is obtained by dB summing over 401 equally spaced frequency samples in the 10 kHz – 2 MHz band. It is conjectured that increasing the number of members in the canonical set would increase the

accuracy of the identification algorithm. The basis set of NEXT PSDs for a T1 disturber is shown in Figure 5. Basis sets for ISDN, HDSL, ADSL, 2B1Q SDSL, and HDSL2 were also created but are not displayed here.

In order to better describe the proposed technique, we will show examples of the single disturber case first, and then we will extend our technique to the case of multiple disturbers.

3.1 *Single disturber case*

For the case of a single disturber, the measured crosstalk PSD is correlated as described in the last subsection with each of the basis PSDs, and the identification is simply the type of crosstalker which has the highest correlation. In the examples here, most common DSL types are simulated: ISDN Basic Rate Interface (BRI), HDSL, T1, ADSL, 400 kbps SDSL, 1040 kbps SDSL, 1552 kbps SDSL, and HDSL2. All transmit system PSDs are as defined in the Spectrum Management Standard, T1.417 [3]. ADSL and HDSL2 have different PSDs upstream and downstream.

An unknown disturber's NEXT PSD is shown in Figure 6. It's calculated correlation with each member of each DSL crosstalk basis set is given in Table 2. The DSL with the highest correlation and thus the identity of the unknown disturber is correctly identified as 1552 kbps SDSL.

Another unknown disturber's NEXT PSD is shown in Figure 7. It's calculated correlation with each member of each DSL crosstalk basis set is given in Table 3. The DSL with the highest correlation and thus the identity of this unknown disturber is correctly identified as downstream ADSL.

Many other cases have been run and its been found that the DSL type of a single disturber is identified correctly in almost all cases. It is difficult to determine the overall accuracy

of the identification algorithm until we have more field data that includes effects such as background noise.

3.2 *Mixed crosstalk case*

The case of mixed crosstalk arises when at least two different services are present in a binder [11]. If the measured crosstalk PSD consists of the contribution of different kinds of disturbers, the identification algorithm proposed in Section 3.1 is not able to identify the whole set of crosstalkers all at once but would identify the strongest interferer only.

In order to overcome this limitation, we propose a frequency-domain onion peeling technique based on spectral subtraction methods [12], [13], [14]. Spectral subtraction is a method that was originally proposed in speech and music processing for the restoration of the power spectrum of a signal observed in additive noise through subtraction of an estimate of the average noise spectrum from the noisy signal spectrum.

Focusing on the crosstalk received on a single pair, the subscript k in equation (2.1) is dropped and $y(m) = r(m) + n(m) + \sum_i h_i(m)d_i(m)$ is the noisy received signal in the sampled-time domain, where $r(m)$ is the received message signal, $n(m)$ is additive background noise, and $y(m)$ is the noisy observation, respectively. To simplify further, define each crosstalk component as $c_i(m) = h_i(m)d_i(m)$ so that the composite received crosstalk is $c(m) = \sum_i c_i(m) = \sum_i h_i(m)d_i(m)$. Then ignoring the background noise and transforming to the frequency domain, $Y(f) = R(f) + C(f)$. In its original formulation, power spectrum subtraction is defined as in the following:

$$\left|\hat{R}(f)\right|^2 = \left|Y(f)\right|^2 - \overline{\left|C(f)\right|^2} \tag{3.2.1}$$

where $\left|\hat{R}(f)\right|^2$ is an estimate of the signal PSD, $\left|Y(f)\right|^2$ is the *instantaneous* PSD of the noisy observation, and $\overline{\left|C(f)\right|^2}$ is the time-averaged noise spectra. The basic assumption is that the noise is a slowly varying process so that averaging would not smear the noise spectrum.

Let $c(m) = c_1(m) + c_2(m)$ be a composite crosstalk constituted of two crosstalk terms pertaining to two different DSL systems. Let us also assume that the identification algorithm proposed in Section 3.1 was able to identify the strongest disturber that generated crosstalk $c_1(m)$ and, therefore, to obtain an estimate of its PSD $\left|\hat{C}_1(f)\right|^2$. Basically, the composite crosstalk $c(m)$ can be viewed as a noisy observation of the useful signal $c_2(m)$ embedded in the noise $c_1(m)$. Since the output of the crosstalk identification algorithm of Section 3.1 is a true PSD obtained on the basis of a PSD mask and an estimated pair-to-pair coupling function, there is no need to perform an averaging operation on the estimated PSD of the strongest crosstalker (noise) $\left|\hat{C}_1(f)\right|^2$. Moreover, the instantaneous PSD of the noisy observation $\left|Y(f)\right|^2$ (necessary in the original formulation of the problem because of the non-stationary nature of speech and music signals) can be replaced in our case by the measured PSD $\left|C_0(f)\right|^2$. Therefore, the power spectrum subtraction for crosstalk identification can be defined as in the following:

$$\left|\tilde{C}_2(f)\right|^2 = \left|C_0(f)\right|^2 - \left|\hat{C}_1(f)\right|^2 \tag{3.2.1a}$$

The residual PSD $\left|\tilde{C}_2(f)\right|^2$ so obtained is then fed to the crosstalk identification algorithm that is now able to unveil the nature of the second disturber and estimate its PSD $\left|\hat{C}_2(f)\right|^2$.

Due to the great variations in the pair-to-pair coupling functions, spectral subtraction can result in negative estimates of the power spectrum. Power spectra are non-negative functions of

frequency, and any negative estimate of these variables should be mapped into a non-negative value. To avoid negative estimates, the power spectrum is post processed using a mapping function $T[\cdot]$ of the form:

$$T\left[\left|\tilde{C}_2(f)\right|^2\right] = \begin{cases} \left|\tilde{C}_2(f)\right|^2, & \text{if } \left|\tilde{C}_2(f)\right|^2 > \beta\left|C_0(f)\right|^2 \\ F\left[\left|C_0(f)\right|^2\right] & \text{otherwise} \end{cases} \tag{3.2.2}$$

For example, in our analysis we found a good value of β is 0.1, so if the estimate $\left|\tilde{C}_2(f)\right|^2$ is not greater than $0.1 \cdot C_0(f)$, then $\left|\tilde{C}_2(f)\right|^2$ is set to some function of the noisy observation $\left|C_0(f)\right|^2$. The simplest choice for the function $f[\cdot]$ is $F[\left|C_0(f)\right|^2] = \textit{noise floor} = -140\,\text{dBm/Hz}$. Another possible choice could be $F[\left|C_0(f)\right|^2] = \beta\left|C_0(f)\right|^2$. A flow chart for implementing the crosstalk identification algorithm is given in Figure 8. Its been found by simulations that overall accuracy is enhanced by retaining and using identified crosstalkers only if the maximum crosstalk correlation is greater than a certain threshold, as shown in Figure 8. An example of the technique follows.

Consider the measured mixed crosstalk given in Fig. 9 that happens to be a mixture of crosstalk from SDSL @1040 kbps and HDSL. The crosstalk identification algorithm yields the results given in Table 4. The identification routine first identifies the strongest disturber as SDSL @1040 kbps. On the next iteration it identifies HDSL as the second stongest disturber. Finally on the third iteration, the maximum correlation of the remainder NEXT is less than 0.90, the set threshold.

The use of spectral subtraction in its basic form (3.2.1), (3.2.1a) may cause deterioration in the quality and the information content of the residual crosstalk PSD. In the literature, there are a number of variants of spectral subtraction that aim to provide consistent performance

improvement across a range of SNRs. In particular, we mention non-linear spectral subtraction methods that utilize estimates of the local SNR, and the observation that at a low SNR *oversubtraction* can produce improved results. The non-linear variant of spectral subtraction can be expressed in the following form:

$$\left|\tilde{C}_2(f)\right|^2 = \left|C_0(f)\right|^2 - \alpha(SNR(f)) \cdot \left|\hat{C}_1^{NL}(f)\right|^2 \tag{3.2.3}$$

where $\alpha(SNR(f))$ is an SNR-dependent subtraction factor, and $\left|\hat{C}_1^{NL}(f)\right|^2$ is a non-linear estimate of the noise spectrum. For example, in [14] it has been proposed that:

$$\alpha(SNR(f)) = \left(1 + \frac{sd\left(\left|\hat{C}_1(f)\right|^2\right)}{\left|\hat{C}_1(f)\right|^2}\right) \tag{3.2.4}$$

$$\left|\hat{C}_1^{NL}(f)\right|^2 = \frac{\underset{over\ M\ frames}{Max}\left(\left|\hat{C}_1(f)\right|^2\right)}{1 + \gamma\, SNR(f)} \tag{3.2.5}$$

where $sd(\cdot)$ is the standard deviation of the noise at frequency f and γ is a design parameter. As (3.2.5) shows, as the SNR decreases the output of the non-linear estimator approaches $Max\left(\left|\hat{C}_1(f)\right|^2\right)$, and as the SNR increases it approaches zero.

Remark (On the relationship between spectral subtraction and Wiener filtering). The spectral subtraction equation can be expressed as the product of the noisy signal spectrum and the frequency response of a spectral subtraction filter as:

$$\left|\hat{R}(f)\right|^2 = \left|Y(f)\right|^2 - \overline{\left|C(f)\right|^2} = H(f)\left|Y(f)\right|^2 \tag{3.2.6}$$

where the frequency response of the spectral subtraction filter is defined as:

$$H(f) = 1 - \frac{\overline{|C(f)|^2}}{|Y(f)|^2} = \frac{|Y(f)|^2 - \overline{|C(f)|^2}}{|Y(f)|^2} \qquad (3.2.7)$$

The spectral subtraction filter *H(f)* is a zero-phase filter, with its magnitude response in the range $0 \le H(f) \le 1$. The filter acts as an SNR-dependent attenuator. The attenuation at each frequency increases with the decreasing SNR, and conversely decreases with increasing SNR.

The least mean squared error linear filter for noise removal is the Wiener filter. The implementation of the Wiener filter requires the power spectra (or equivalently the correlation functions) of the signal and the noise process. The Wiener filter is based on *ensemble average spectra* of the signal and the noise, and the averaging operations are taken across the ensemble of different realizations of the signal and noise processes. On the other hand, the spectral subtraction filter, uses *instantaneous spectra* of the noisy observation and the *time averaged spectra* of the noise. This is necessary since in spectral subtraction only one realization of the noise process is available.

The main attraction of spectral subtraction is its relative simplicity since it only requires an estimate of the noise power spectrum. This is also its fundamental limitation since it does not utilize the statistics of the signal process and so it may use too little priori information. However, for an ergodic process, the time-averaged spectrum approaches the ensemble averaged spectrum, so that the spectral subtraction filter asymptotically approaches the Wiener filter. This property does not hold when processing speech and music signals since they are intrinsically non-stationary (and, therefore, non-ergodic). However, when spectral subtraction is applied to the present case of crosstalk identification, the quantities involved are true PSDs and not instantaneous or time-averaged ones. Therefore, the implementation of spectral subtraction may be viewed as a sort of optimal Wiener filtering. This interpretation may explain why spectral

subtraction seems to perform very well when applied to successive crosstalk identification. Also, an analysis in the next Section shows that the spectral subtraction method here is effective for crosstalk identification in the case of mixed crosstalkers. The major limitation we have encountered is the non-linear processing distortion due to the necessity of mapping negative values into non-negative values. This distortion increases at every iteration when equation (3.2.2) is implemented and limits the accuracy of the algorithm to the identification of up to a small number of different crosstalker types. From a practical point of view, this does not look as a major limitation since it is very unlikely that more than a few interferers cause performance degradation in DSL systems. Finally, the benefit of using non-linear spectral subtraction for improving the accuracy of the identification algorithm is currently being investigated by the authors.

4. A Novel Method of Adaptive Crosstalk Cancellation

The frequency domain methodology described in Section 3 is useful for quantizing the types of DSLs creating crosstalker. In this Section, we will show how the technique described in the previous Section can be embedded in an DSL receiver in a method that should enhance the identification of the set of interfering services. Moreover, the proposed receiver structure is able to exploit the information on the kind of disturbers for crosstalk cancellation via linear MMSE prediction. The case of multitone receivers and will be addressed, but the analysis could be extended to the case of singlecarrier receivers.

4.1 *Identification in multitone receivers*

A block diagram of a generic discrete multitone (DMT) DSL system [1] with N carriers is shown in Figure 9. The L data bits $b_i(l)$, $0 \leq l \leq L\text{-}1$, are mapped into P constellation symbols by the P modulators. Let the discrete complex frequency domain symbol $D_i(m)$ denote the output of

the m-th modulator ($0 \le m \le P$-1), with time interval index i denoting the i-th DMT-block. For the i-th DMT-block, the IDFT output is the given by

$$d_i(k) = \frac{1}{N}\sum_{m=0}^{N-1} D_i(m)\, e^{j2\pi mk/N}, \qquad k = 0, 1, \cdots, N-1 \tag{4.1.1}$$

The samples $d_i(k)$ form the input to the transmit pulse shaping filter. Prior to being filtered, v cyclic-prefix samples are appended to the DMT symbol in order to eliminate ISI due to inter-block interference introduced by the dispersive channel. Finally, the i-th DMT-block $x_i(t)$ is transmitted over the channel.

The received signal is corrupted by the noise process $c(t)$. In DSL environments, this noise is composed of two terms: white Gaussian noise (thermal noise) and colored noise (crosstalk). As far as the statistical distribution of the crosstalk amplitude is concerned, the Gaussian approximation is a reasonable one. A confirmation of the validity of this assumption can be found, for example, in [15], [16].

At the receiver, the noisy channel output is sampled at $t = kT$. The discrete sampled signal containing the samples of the i-th DMT block (without loss of generality, the sampling period is normalized to T=1) can be written as

$$r_i(k) = \sum_{j=0}^{M-1} h(j)\, x_i(k-j) + c_i(k) = \sum_{j=0}^{M-1} h(j)\, d_i(k-j) + c_i(k) = h(k) \otimes d_i(k) + c_i(k) \tag{4.1.2}$$

where $\otimes$ denotes convolution, $h(j)$ is the value of the equivalent T-sampled channel impulse response at position j, and $c_i(k)$ is the additive colored noise affecting the i-th DMT block. In order to recover the transmitted signal from the k-th subchannel of the i–th DMT block, the cyclic prefix samples are removed from $r_i(k)$, and the resulting block of N samples is fed to the DFT processor. The frequency domain symbols at the output of the DFT can be expressed as follows:

$$R_i(n) \equiv DFT[r_i(k)] = DFT[h(k)] \cdot DFT[d_i(k)] + DFT[c_i(k)] = \\ = H(n)D_i(n) + C_i(n) \tag{4.1.3}$$

A start-up sequence is employed to obtain a set of N estimates of the channel transfer function:

$$\hat{H}(j) = \frac{R_i(j)}{D_i(j)}, \quad j \in \mathcal{A} \tag{4.1.4}$$

Therefore, dividing the samples in (4.1.3) by the corresponding channel estimates, we obtain:

$$Q_i(n) \equiv \frac{R_i(n)}{\hat{H}(n)} = D_i(n)\frac{H(n)}{\hat{H}(n)} + \frac{C_i(n)}{\hat{H}(n)} \cong D_i(n) + \frac{C_i(n)}{\hat{H}(n)}, \quad 0 \le n \le N-1 \tag{4.1.5}$$

The decision variables $Q_i(n)$ are fed to a memoryless decision device and the estimate $\hat{D}_i(n)$ of the transmitted constellation symbol is obtained. After demodulation, the L data bits of the i-th DMT-block $\hat{b}_i(l)$, $0 \le l \le L$-1, are recovered.

It is evident from (4.1.5) that a description, in the frequency domain, of the crosstalk realization affecting the i-th block is available from the set of N decision variables $Q_i(n)$, $0 \le n \le N$-1. An estimate of $C_i(n)$ can be obtained by subtracting the decisions $\hat{D}_i(n)$ from the decision variables $Q_i(n)$ and, then, by multiplying by the channel estimates $\hat{H}(n)$ (see the block diagram in Figure 10):

$$\hat{C}_i(n) = \left(Q_i(n) - \hat{D}_i(n)\right)\hat{H}(n), \quad 0 \le n \le N-1 \tag{4.1.6}$$

Under the assumption of correct decisions, the N quantities $\left|\hat{C}_i(n)\right|^2$ can therefore be considered an approximation of the samples (at the carrier frequencies) of the PSD of the actual colored noise realization in the frequency band occupied by the DMT-system. More in detail, $\left|\hat{C}_i(n)\right|^2$ represents the *periodogram* of the crosstalk realization obtained on the basis of a rectangular window of N samples. As it is well known [17], the periodogram is asymptotically unbiased but

not a consistent estimate of the actual PSD since its variance does not tend to zero for large N. Moreover, the periodogram suffers also from spectral leakage effects due to the windowing of the data. However, a periodogram of the crosstalk is available for every received DMT-block so that averaging methods can be employed to reduce the variance of the periodogram estimate. Among these methods, we can recall Bartlett's, Welch's and Balckman-Tuckey's methods [17], [18]. An efficient way to reduce the effects of spectral leakage is to perform Kaiser windowing on each periodogram. This would imply the necessity of windowing the data in the time domain and, therefore, is not computationally efficient since it is the periodogram, i.e. the DFT of the windowed crosstalk, that is already available (see (4.1.6)). Some preliminary simulations that we indicate that there may be no substantial performance improvement by computing modified periodograms, so that Kaiser windowing is not performed in our system. On the other hand, it averaging the periodogram over a number of DMT-blocks can greatly improve the accuracy of the PSD estimate.

Once that an estimate of the PSD is available, it is fed to the "Crosstalk Identification" block that performs identification as described in Section 3 (see again Figure 10). The information on the identified crosstalker may then be exploited in two ways: it may be provided to a "third party" for spectrum management and it may also be used for interference cancellation purposes as described in the following Section.

Remark (Validity of the assumption of correct decisions).

During the initialization phase, a long startup string of a great number of DMT-blocks of known symbols are transmitted over the channel. This allows a high accuracy in estimating the crosstalk PSD, and the assumption of correct decisions made earlier is reasonable.

4.2 *A method of crosstalk cancellation and successive identification*

In the receiver structure proposed in this section, the successive spectral subtraction is performed by a modification of the Crosstalk Identification block defined in Section 3. First, only the strongest interferer is identified. Then, in order to achieve identification of the whole set of disturbers, a technique is proposed that exploits correlations of the identified crosstalker types to aid in performing successive cancellation at the receiver in the time domain prior to DMT processing. A key component here is the block that quantizes the crosstalker type to one of a limited set, enabling accurate determination of crosstalk correlation and subsequent predictive cancellation.

A meaningful performance improvement can be obtained by whitening the colored component of the received sequence, so as to obtain an enhancement of the SNR at the decision point. The improvement obtained by removing the correlation of the crosstalk will be higher when the crosstalk is very correlated, *i.e.*, in the case of crosstalk from a relatively slow-speed DSL such as ISDN BRI coupling into a relatively high-speed DSL such as 1552 kbps SDSL, and less effective when the crosstalk is only slightly correlated.

As in standard PDFE schemes [19], an effective strategy to whiten a colored sequence is to use a linear predictor of order p, implemented as a finite impulse response filter, and subtracting from the received sequence $r_i(k)$ the p-th order linear prediction of the colored component. The linear prediction $\tilde{c}_i(k)$ of the colored noise sequence $c_i(k)$ based on the past p samples of the estimated crosstalk can be expressed as follows:

$$\tilde{c}_i(k) = \sum_{j=1}^{p} a_j^{(p)} \hat{c}_i(k-j) \tag{4.3.1}$$

where $\hat{c}_i(k)$ is the estimated disturbing sequence and $a_j^{(p)}$, j=1, 2, ..., p, are weighting coefficients.

The samples of the noise sequence $c_i(k)$ can be obtained by subtracting the useful part of the received signal from the received sequence (see equations (4.1.2) and (4.1.3)):

$$c_i(k) = r_i(k) - h(k) \otimes d_i(k) = r_i(k) - IDFT[H(n)D_i(n)] \tag{4.3.2}$$

Since both the sequences $H(n)$ and $D_i(n)$ are not available at the receiver, only an estimate $\hat{c}_i(k)$ of the noise realization can be obtained on the basis of channel estimates and symbol decisions:

$$\hat{c}_i(k) = r_i(k) - IDFT[\hat{H}(n)\hat{D}_i(n)] \tag{4.3.3}$$

The optimum (in an MMSE sense) coefficients $a_j^{(p)}$, j=1, 2, ..., p, of the predictor of order p can be directly obtained by solving the following Yule-Walker equations:

$$\begin{vmatrix} \varphi(0) & \varphi(-1) & \varphi(-2) & \cdots & \varphi(-p+1) \\ \varphi(1) & \varphi(0) & \varphi(-1) & \ddots & \varphi(-p+2) \\ \varphi(2) & \varphi(1) & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \varphi(-1) \\ \varphi(p-1) & \varphi(p-2) & \cdots & \varphi(1) & \varphi(0) \end{vmatrix} \begin{vmatrix} a_1^{(p)} \\ a_2^{(p)} \\ a_3^{(p)} \\ \vdots \\ a_p^{(p)} \end{vmatrix} = \begin{vmatrix} \varphi(1) \\ \varphi(2) \\ \varphi(3) \\ \vdots \\ \varphi(p) \end{vmatrix} \tag{4.3.4}$$

where $\varphi(k) \equiv E\{c^*(m)c(m+k)\}$ is the autocorrelation function of the disturbing sequence $c_i(k)$. The correlation of the disturbance $c_i(k)$ can be obtained from the IDFT of the PSD of the identified disturber available from the Crosstalk Identification block. As already mentioned at the end of Section 4.1, the Crosstalk Identification block only identifies the strongest crosstalker and does not attempt to identify the other ones by spectral subtraction. Therefore, at this point $\varphi(k)$ represents the correlation of the strongest disturber only. It will be shown shortly how estimates of the crosstalker types, and therefore the crosstalker correlations, will be successively quantized and used to identify multiple disturber types.

Once that the crosstalk realization $\hat{c}_i(k)$ and the optimum coefficients $a_j^{(p)}$ are available, the p-th order linear MMSE prediction of the crosstalk $\tilde{c}_i(k)$ can be obtained as in equation (4.3.1)

and subtracted from the received sequence. In so doing, we obtain (see the block diagram in Figure 11):

$$y_i(k) = r_i(k) - \tilde{c}_i(k) = h(k) \otimes d_i(k) + c_i(k) - \tilde{c}_i(k) = h(k) \otimes d_i(k) + n_i(k) \tag{4.3.5}$$

In the above equation, the sequence $n_i(k) \equiv c_i(k) - \tilde{c}_i(k)$ constitutes the realization of the residual crosstalk affecting the system and exhibits the following variance:

$$\sigma_n^2 \equiv \sigma_c^2 \prod_{i=1}^{p} \left(1 - \left|a_i^{(p)}\right|^2\right) \tag{4.3.6}$$

where σ_c^2 denotes the variance of the sequence $c_i(k)$. The SNR gain due to the partial whitening of the noise sequence is then given by

$$G_{SNR} \equiv \frac{\sigma_c^2}{\sigma_n^2} = \frac{1}{\prod_{i=1}^{p} \left(1 - \left|a_i^{(p)}\right|^2\right)}. \tag{4.3.7}$$

At this point in the cycle the achieved crosstalk cancellation (whitening) is not complete since only the correlation of the strongest interferer has been used to compute the optimum linear predictor, so that only this interferer has been removed from the received signal. This ensures that, in the following DMT-blocks, the N quantities $\left|\hat{C}_i(n)\right|^2$ will now represent the periodogram of the residual crosstalk, i.e. the crosstalk due to all the remaining interferers. The estimate of the PSD of the remaining crosstalk will then be fed to the Crosstalk Identification block so that the next strongest interferer can be identified. The next strongest interferer has been identified, and it's correlation is identified as one of the quantized set of known crosstalk disturber types. Then, the next strongest interferer's correlation is summed to the one pertaining to the previously identified disturber, a new set of optimum coefficients is computed and the effects of the two strongest interferes are then removed. This successive identification continues on a DMT-block

basis and ends when the residual noise sequence is approximately white, or when the gain sequence G_{SNR} approaches unity.

Remark (On the problem of ambiguous identification).

Since crosstalk is only observed in the band of the disturbed service, there might be some ambiguity in the identification process. This might happen if two or more disturbers generate crosstalk that exhibits similar PSDs in the observed bandwidth. This situation arises if the disturbers have similar transmit PSDs and are subject to similar pair-to-pair couplings in the observed bandwidth. Although it is possible that in some frequency bands different services may have similar PSDs, it is not very likely that they are subject to similar pair-to-pair coupling functions. From this point of view, the high variability of the pair-to-pair coupling functions can be considered as a form of diversity that reduces the chance of ambiguity. The price to pay for this diversity benefit is the necessity of a large basis set when computing the correlation coefficients.

5. Conclusions

This paper presented a method of identifying the types of DSL generating crosstalk. This method can be applied independently to any DSL line to identify crosstalk for spectrum management purposes. It could also be embedded into any single receiver. The method has been found to be very accurate in identifying a single crosstalk disturber type. It was extended to identifying multiple disturber types, and then a novel receiver structure was proposed that exploits the knowledge of DSL disturber type to identify the time correlation of the received crosstalk to use in predictive cancellation.

6. References

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Figure Captions

Figure 1 - Twisted pair cabling near-end crosstalk (NEXT). Typically $12 \leq N \leq 100$
Figure 2 - Power-sum NEXT couplings
Figure 3- Pair-to-pair NEXT couplings.
Figure 4 - Canonical set of pair-to-pair NEXT couplings
Figure 5 - Basis set of T1 NEXT couplings
Figure 6 - Unknown disturber NEXT PSD, example 1
Figure 7 - Unknown disturber NEXT PSD, example 2
Figure 8 - Crosstalk identification flow chart
Figure 9 - Mixed disturber NEXT PSD, example 3
Figure 10 - Block diagram of a generic DMT receiver. The estimates G_i of the channel at each tone frequency i (i=1, ..., N) are available on a block-per-block basis from then frequency domain equalizer.
Figure 11 - The technique for crosstalk identification in multitone systems
Figure 12 - Method of crosstalk identification and cancellation in multitone systems

Table Captions

Table 1. Loose categorization of techniques for handling multi-pair cables with crosstalk as multiuser channels
Table 2. Correlation results, example 1
Table 3: Correlation results, example 2.
Table 4: Results for mixed crosstalk case, example 3

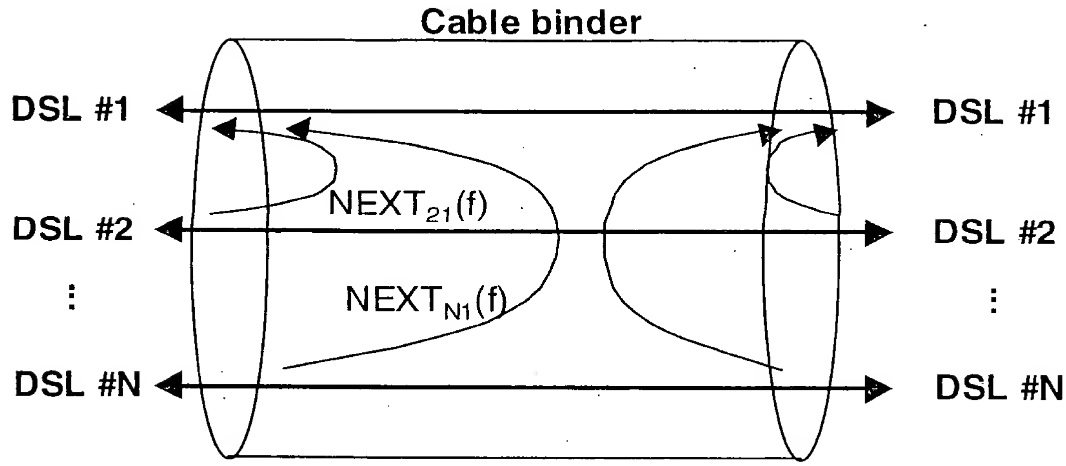


Figure 1 - Twisted pair cabling near-end crosstalk (NEXT). Typically $12 \leq N \leq 100$

Area	Off-line estimation	Run-time applications
Usage	Dynamic spectrum management, spectral planning	Transceiver optimization, multiuser detection and cancellation
Domain	Frequency domain oriented	Time domain oriented
Detect	Identify DSL types and crosstalk impacts	Identify received sampled crosstalk sequences, and pulse arrival times
Single Line	Simple dynamic spectrum management	Multiuser receiver
Multi-line	Joint dynamic spectrum management	Vector transceivers
Operational	Compliance verification, trouble shooting, maintenance diagnoses	Alarms, automated real-time problem solving

Table 1. Loose categorization of techniques for handling multi-pair cables with crosstalk as multiuser channels

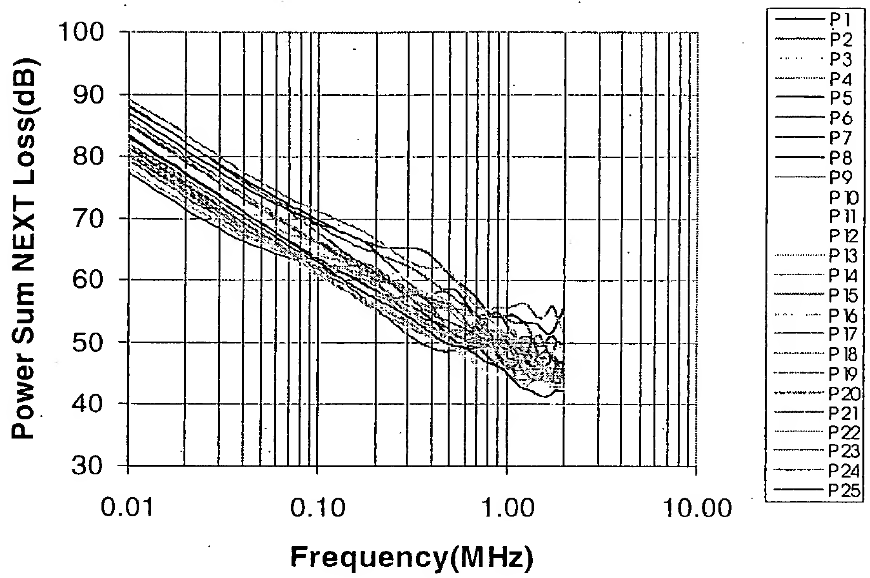


Figure 2 - Power-sum NEXT couplings

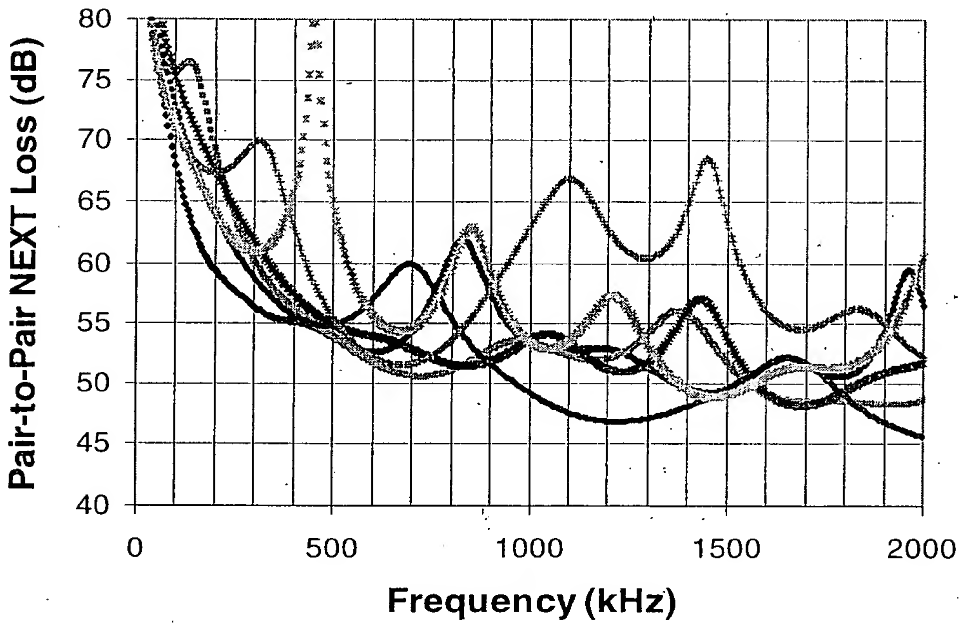


Figure 3- Pair-to-pair NEXT couplings.

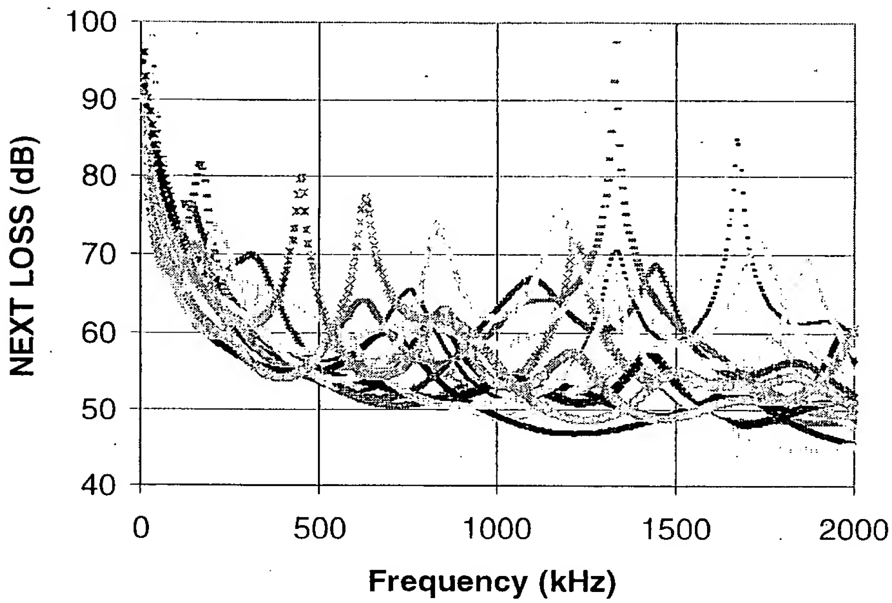


Figure 4 - Canonical set of pair-to-pair NEXT couplings

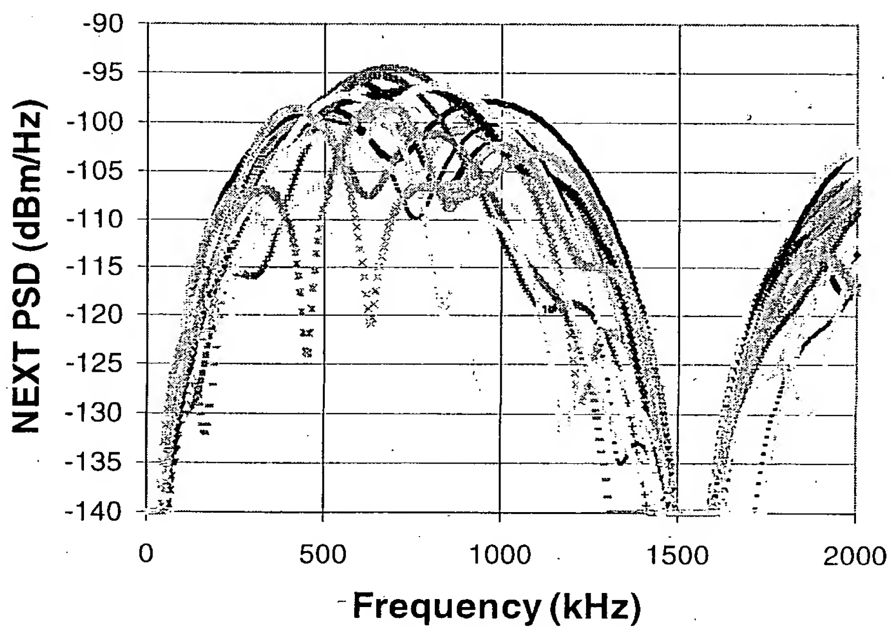


Figure 5 - Basis set of T1 NEXT couplings

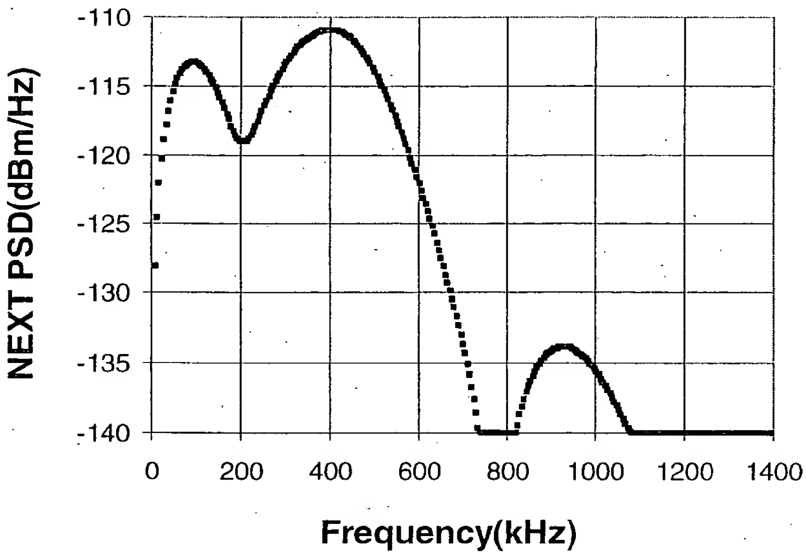


Figure 6 - Unknown disturber NEXT PSD, example 1

Basis Coupling	ISDN BRI	HDSL	T1	ADSL Down	ADSL Up	SDSL 400	SDSL 1040	SDSL 1552	HDSL2 Down	HDSL2 Up
1	0.0324	0.1823	0.3225	0.1947	0.2427	0.3052	0.2976	0.7503	0.6244	0.0888
2	0.0257	0.2582	0.0009	-0.1045	0.3102	0.2526	0.4596	0.9022	0.637	0.0861
3	0.0351	0.2094	-0.0486	-0.1852	0.2615	0.302	0.2132	0.4523	0.4871	0.1039
4	0.0389	0.1989	0.2199	0.0722	0.2535	0.3036	0.2788	0.7056	0.6259	0.0946
5	0.0315	0.2136	0.0012	-0.1415	0.2645	0.3008	0.4201	0.9124	0.6439	0.0899
6	0.0331	0.1907	0.1528	-0.1465	0.2545	0.3044	0.3726	0.8638	0.637	0.0856
7	0.0297	0.2579	-0.0507	-0.0769	0.2833	0.2911	0.2906	0.7818	0.699	0.1378
8	0.0599	0.1617	0.396	0.0398	0.2301	0.3004	0.3241	0.8039	0.6282	0.0803
9	0.0259	0.3438	0.5703	0.5072	0.3035	0.2492	0.5109	0.8657	0.6328	0.1057
10	0.0273	0.3209	0.4956	0.3835	0.3055	0.2686	0.4642	**0.9776**	0.6718	0.3113
11	0.0309	0.2483	0.3381	0.3841	0.2787	0.2942	0.3842	0.9262	0.6589	0.1137
12	0.05	0.1763	-0.2645	-0.2905	0.2382	0.3009	0.2794	0.771	0.633	0.087
13	0.0258	0.3359	0.7741	0.2253	0.307	0.252	0.4791	0.8263	0.6286	0.1101
14	0.0281	0.2116	-0.1477	-0.2566	0.2768	0.293	0.2737	0.4701	0.5408	0.0912

Table 2. Correlation results, example 1

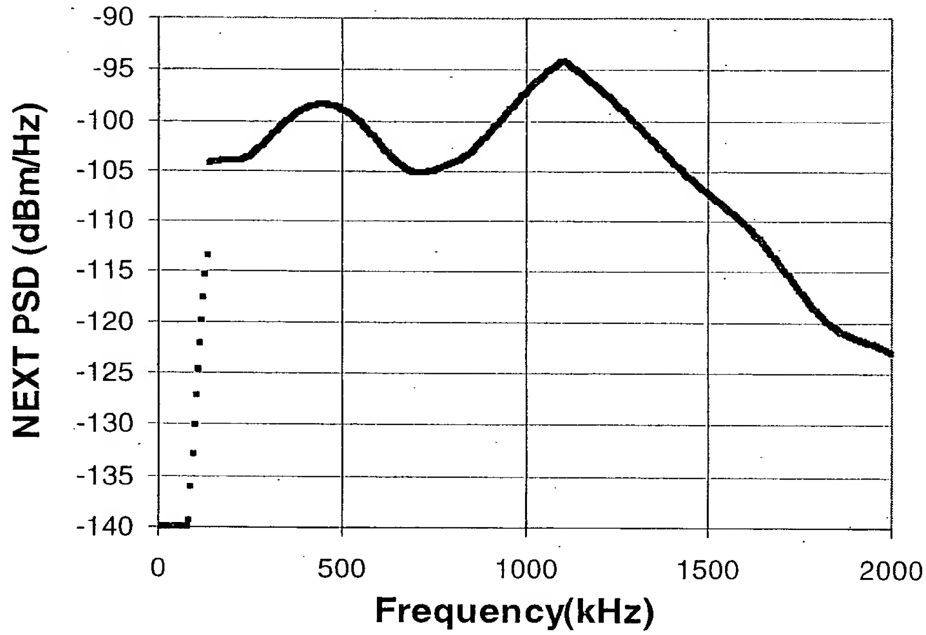


Figure 7 - Unknown disturber NEXT PSD, example 2

Basis Coupling	ISDN BRI	HDSL	T1	ADSL Down	ADSL Up	SDSL 400	SDSL 1040	SDSL 1552	HDSL2 Down	HDSL2 Up
1	-0.1263	-0.1531	0.1797	0.6762	-0.1488	-0.1932	-0.1261	0.0157	0.0241	-0.0991
2	-0.1242	-0.1854	0.0079	0.3648	-0.2038	-0.1926	-0.0703	0.1312	0.0529	-0.0818
3	-0.1266	-0.1688	0.313	0.7028	-0.1603	-0.1942	-0.1581	-0.0782	-0.0807	-0.1159
4	-0.1261	-0.1623	0.1296	0.4366	-0.1548	-0.1909	-0.1397	-0.0119	0.0125	-0.1041
5	-0.1252	-0.1657	0.0506	0.4303	-0.1632	-0.1974	-0.0994	0.1246	0.0505	-0.093
6	-0.1255	-0.1552	0.6056	0.9228	-0.1567	-0.1965	-0.1021	0.0863	0.0435	-0.0914
7	-0.1255	-0.1927	-0.0853	-0.0648	-0.1762	-0.1981	-0.181	0.082	0.0062	-0.1382
8	-0.1157	-0.14	0.49	0.8042	-0.14	-0.1798	-0.1017	0.0568	0.0363	-0.0889
9	-0.1249	-0.2219	0.0936	0.1892	-0.1996	-0.1899	-0.0778	0.1015	0.0512	-0.0856
10	-0.1253	-0.2136	0.2077	0.523	-0.1951	-0.195	-0.2051	0.0483	0.0358	-0.2187
11	-0.1255	-0.1876	0.079	0.1361	-0.1729	-0.198	-0.1518	0.0957	0.0408	-0.1155
12	-0.1182	-0.1504	0.0243	0.4099	-0.1452	-0.1816	-0.1273	0.0269	0.0238	-0.0989
13	-0.125	-0.2314	0.5101	0.954	-0.2014	-0.1916	-0.112	0.0639	0.0423	-0.0944
14	-0.1255	-0.1746	0.0932	0.5948	-0.1732	-0.2015	-0.1389	-0.0766	-0.0091	-0.0984

Table 3: Correlation results, example 2.

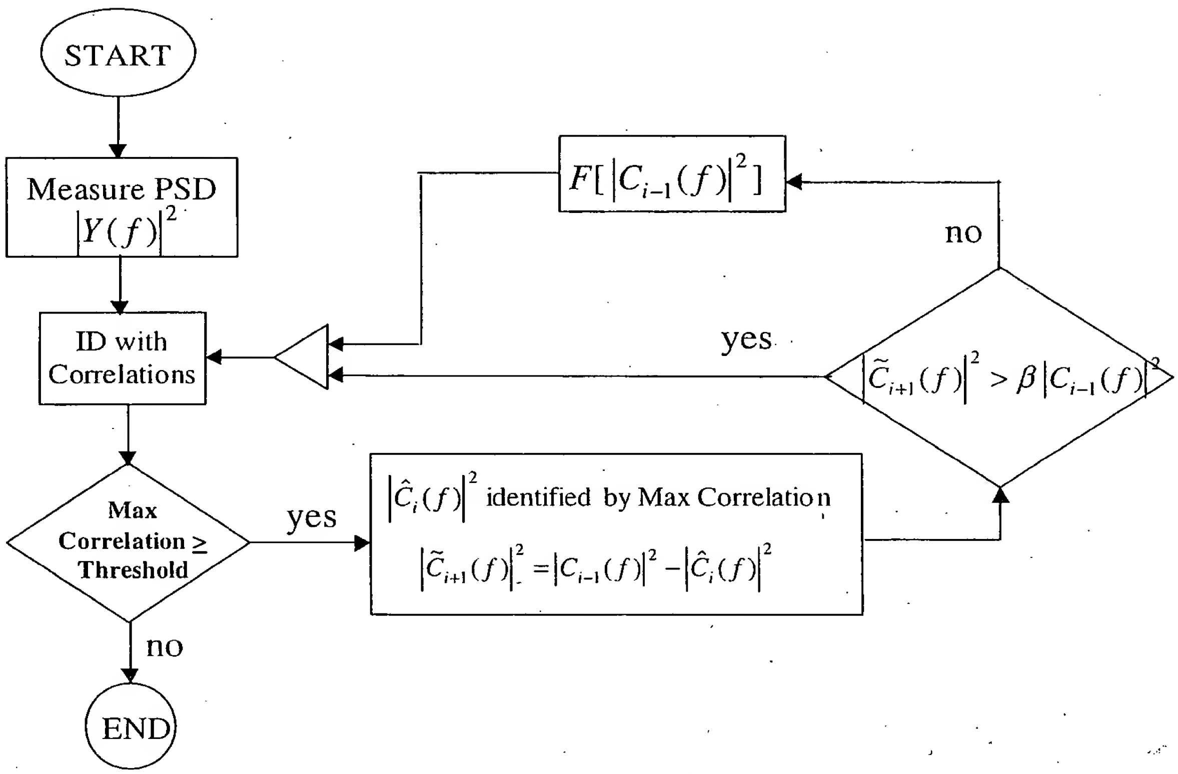


Figure 8 - Crosstalk identification flow chart

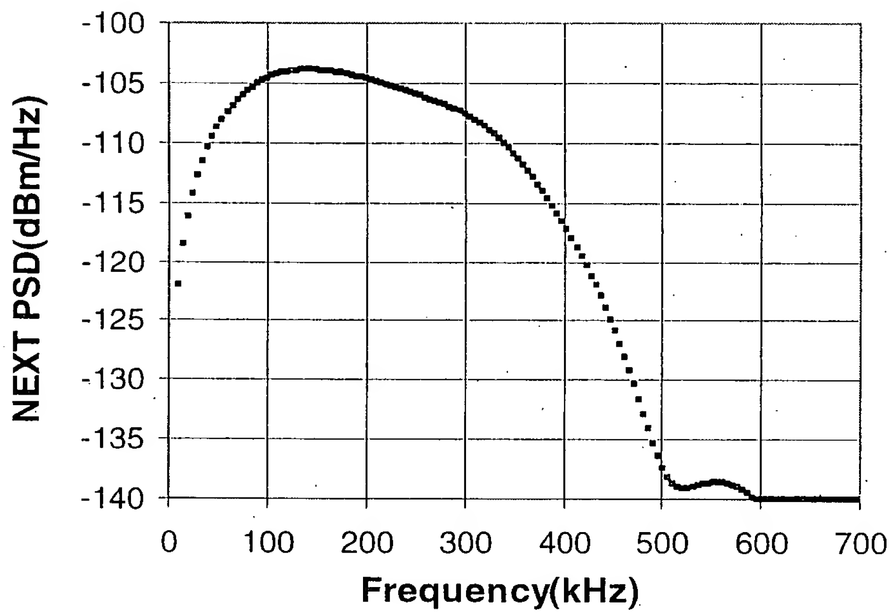
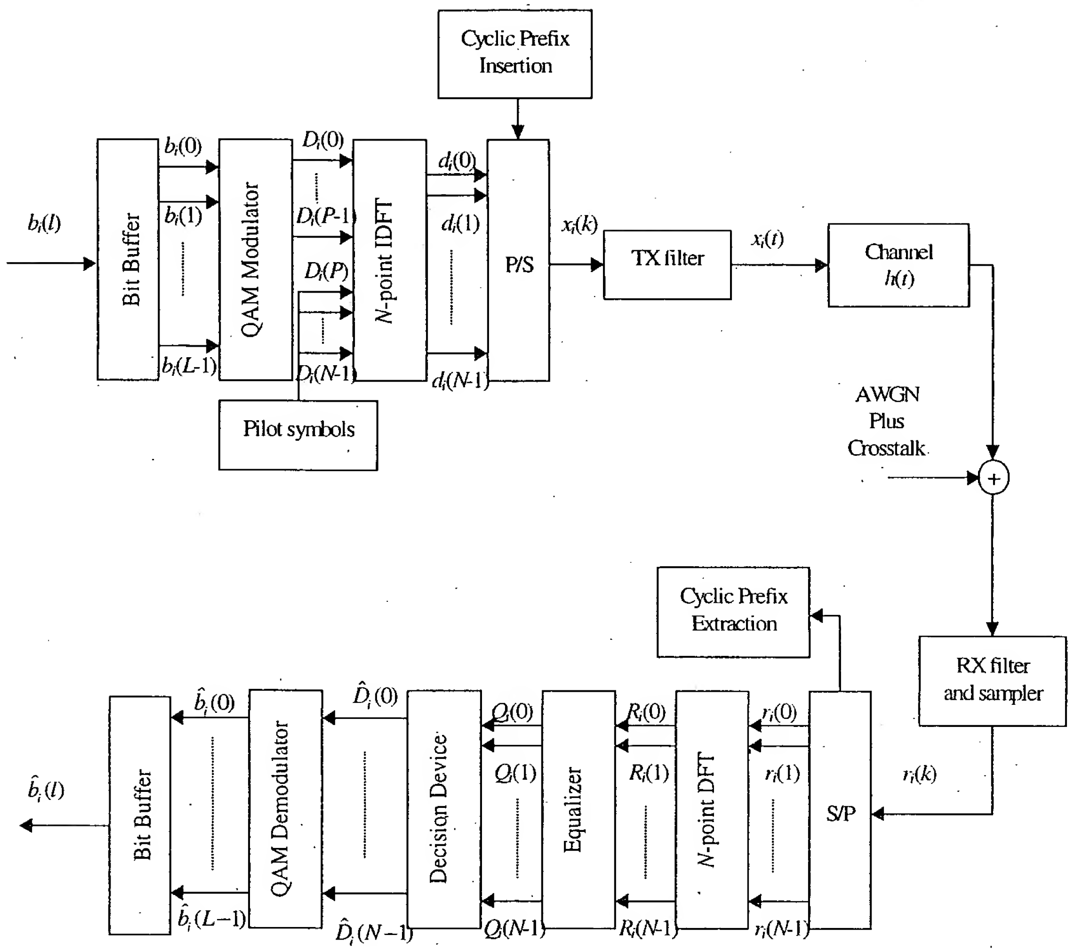


Figure 9 - Mixed disturber NEXT PSD, example 3

Iteration	NEXT Power(dBm)	Max Correlation	DSL Type	coupling #
1	-50.6	0.9719	1040 kbps SDSL	7
2	-51.8	0.9235	HDSL	11
3	-54.0	< 0.90	none	

Table 4: Results for mixed crosstalk case, example 3



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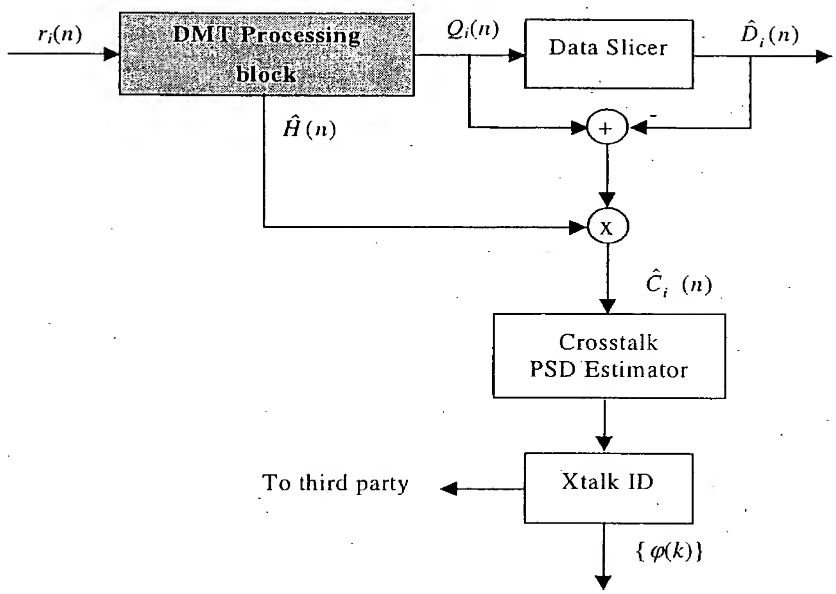

Figure 11 - The technique for crosstalk identification in multitone systems

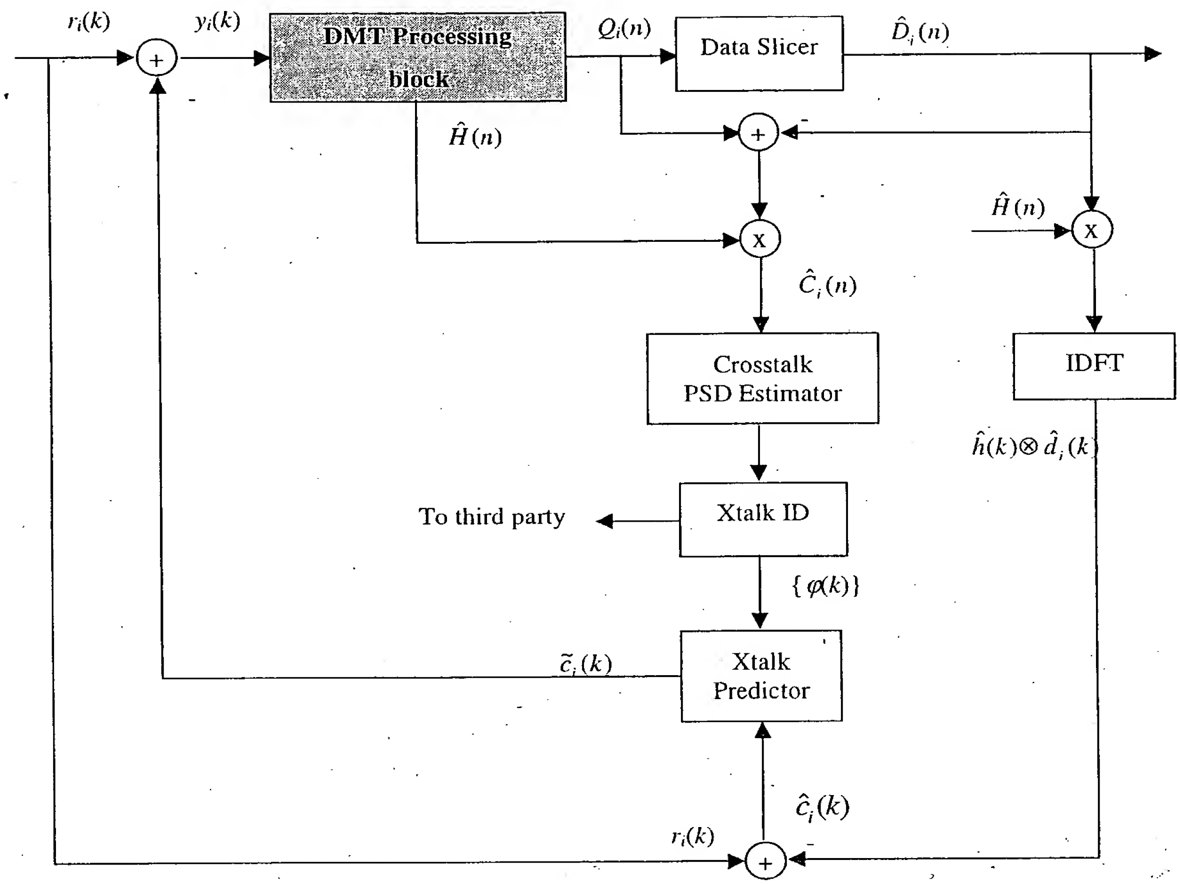

Figure 12 - Method of crosstalk identification and cancellation in multitone systems

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